UNCHS(Habitat)

Earth Construction Technology

Manual on Design and Construction Techniques

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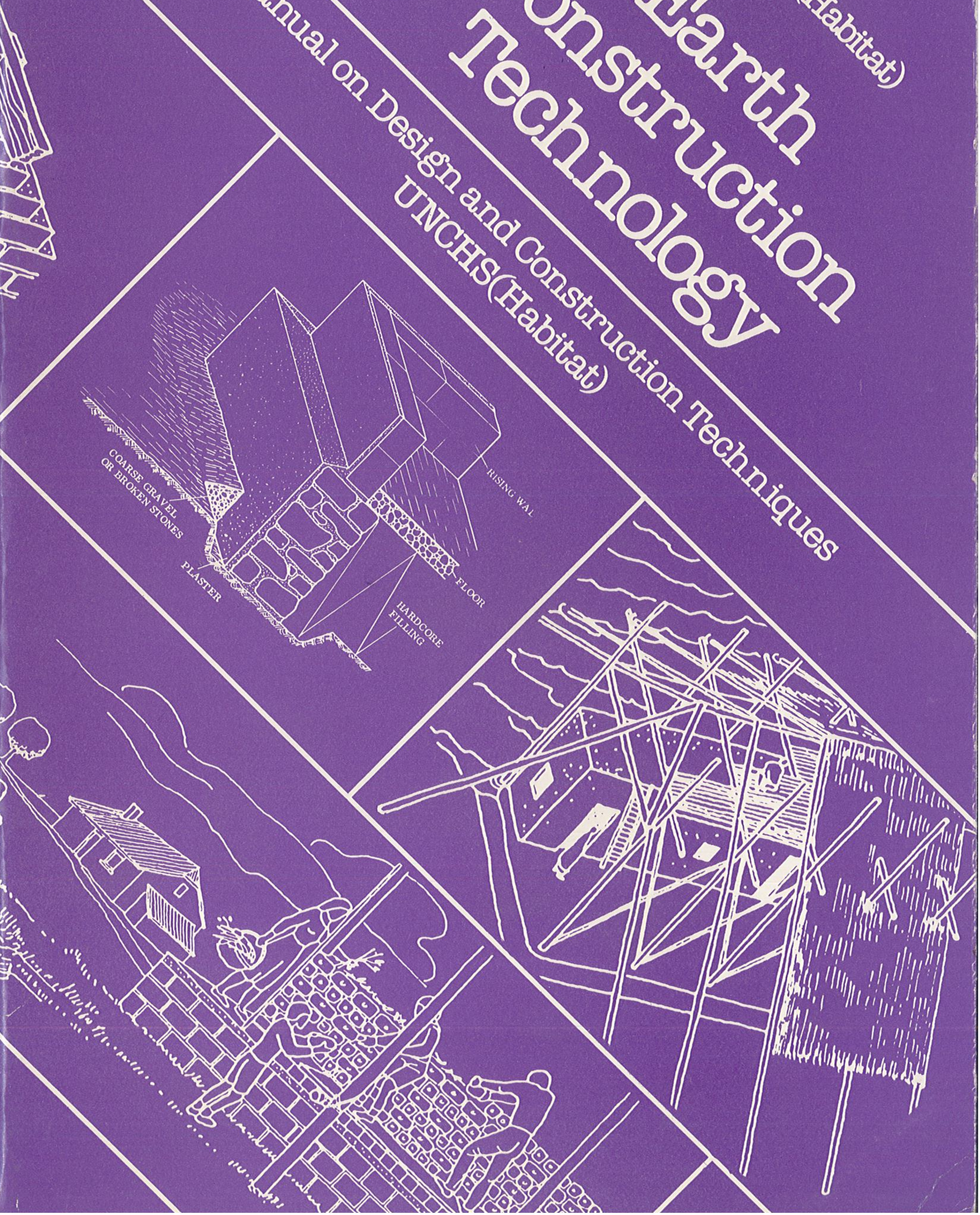

EARTH CONSTRUCTION TECHNOLOGY

MANUAL ON DESIGN AND CONSTRUCTION TECHNOLOGY

United Nations Centre for Human Settlements (Habitat)
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FOREWORD

In most rural areas of the developing countries and in some urban low-income settlements, earth is the main material used for shelter construction. Under these circumstances, earth construction is characterized by dilapidated, temporary and unsafe structures. In fact, living examples of good, durable and attractive earth buildings are hard to come by, while the popularity of the material has dwindled to the extent that, even in circumstances where it should be the obvious choice in rural housing construction, preference has been given to relatively modern materials.

In principle, soil is not restricted to low-cost construction, but, rather, forms the basis of technically sound engineering practice which is comparable to concrete technology or that of any of the popularly adopted building materials. Ultimately, a building material responds to clearly defined functional requirements in the construction process. The merit of earth in construction should be judged by its ability to fulfil a number of construction tasks - notably as a material for walls, floor, renderings and even for roofs. The issue of earth being a low-cost material is incidental and, indeed, an added advantage to these technically viable properties. For this reason, the material should be promoted alongside other conventional materials to the extent that professionals in the construction sector can make a choice for earth in preference over or as an alternative to comparable materials. It is along these lines that the objectives of wide-scale adoption of the material could be achieved while meeting the construction needs of the low-income population.

Following this principle, earth construction faces an obvious disadvantage in comparison with other popularly adopted materials. There is limited knowledge of good earth construction practice. The construction technologies which are predominant in the informal channels for artisan training are defective and inappropriate. In the conventional technical and professional training institutions, there is hardly any coverage of the subject of earth construction apart from basic civil engineering consideration. While architects, town planners, civil engineers, quantity surveyors and numerous sub-professionals in the construction sector have a role to play in promoting the use of earth, the foremost task is to fill a gap in their knowedge, i.e., to provide adequate technical information on earth construction for use by professionals in field implementation projects. It is for this purpose that this set of publications has been provided.

This series of publications on earth construction is made up of four technical manuals, namely, (1) Manual on basic principles of earth application, (2) Manual on production of components, (3) Manual on design and construction techniques, and (4) Manual on surface protection. The four manuals are complementary to each other yet each is presented in a distinct and concise manner to respond to a specific component of the subject.

These manuals are intended for professionals dealing with projects on earth construction and should serve as useful reference material and aids in actual field practice. This current publication will be supplemented by other publications on various aspects of earth construction for the benefit of a wider group of professionals, programme administrators and policy-makers who are concerned with the subject. Eventually, it is expected that all these efforts will contribute to the provision of detailed and simplified manuals for use by the ultimate field worker - the technician or the craftsman.

The preparation of these manuals is based on an extensive project on earth construction technology undertaken by UNCHS (Habitat) in collaboration with the Government of Belgium. UNCHS (Habitat) is deeply grateful to Messrs. Hugo Houben and Guillaud Hubert, who were the principal consultants for the project.

A. Ramachandran

Dr. Arcot Ramachandran
Under-Secretary-General
Executive Director

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I. BASIC CONSIDERATIONS

Chronic damp problems can be avoided by adopting a good approach to the design and execution of the earth structure.

In order for water to take effect, the following three conditions must coexist:

(a) Water must be present on the surface of the building;

(b) There must be an opening in this surface, such as a crack or window, which allows the water to enter;

(c) There must be a force - pressure, gravity of capillary action - facilitating the entry of water into the opening.

The most fragile points in earth structures and most vulnerable to water action and moisture are the bottom of the wall, and the top of the wall. There are other localized weak points as well such as the reveals of openings, parapets of terraces, gargoyles, and bonds between different materials, such as between earth and wood. These are the points which require special care and regular maintenance.

Capillary rise at the base of walls, beginning in the foundations, has several origins, including seasonal changes in the ground-water table, retention of water by the roots of shrubs, defective sewers, a lack of drains for the building, and standing water at the foot of walls. Persistent dampness can bring about a weakening of the base of the walls. The material passes from the solid to the plastic state and the walls can no longer bear loads, increasing the likelihood of collapse. Dampness favours efflorescence by salts attacking the material and causing hollows to form. Insects and rodents attracted by the damp conditions can cause further deterioration to the wall.

Above ground level, the base of the walls may be eaten away for any of the following reasons: water splash from gargoyles, water thrown up by passing vehicles, washing of floors, indoors, surface condensation (morning dew), run-off at the foot of the wall (gutters too close to the wall), surface rendered impermeable (water-tight walkway or rendering) preventing evaporation or encouraging condensation between the earth wall and the water-proof rendering, the growth of parasitical flora (moss) and efflorescence.

Damage can also occur in the following ways:

(a) Water infiltrates through structural cracks (settlement, and shearing) and shrink cracks caused by repeated dry-wet cycles, unfilled holes left by formwork clamps, and by defective mortar joints causing capillary action, and hollowing of walls.

(b) Water runs off at the junction of reveals and earth walls (support, lintel) and infiltrates between the masonry of the reveal or the wooden frame and the soil causing localized deterioration.

(c) Rain and variations in temperature can bring about the decomposition of the material. Clays are washed out, reducing the cohesion of the soil.

(d) When an earth wall is protected with a rendering which prevents the movement of water vapour, condensation on the cold surface of the wall (indoor walls in summer; outside wall in winter) or condensation between the wall and the rendering may cause the wall to deteriorate.

(e) Water may penetrate at the point where floor or roof beams pass through earth walls.

(f) Water runs and gets in where poorly designed gargoyles pass through walls and are unprotected at their entry and exit. Accumulation of earth can stop up gargoyles, resulting in standing water, absorption and capillary action.

(g) Parapets unprotected by a projecting cap or which are cracked or covered with a defective rendering encourage water run-off and infiltration. Objects placed against parapets such as plants requiring watering and poorly drained terraces can cause water and dampness to be retained.

(h) Cracked terraces and damaged surfacing facilitate infiltration.

Like all structures, those built with earth may be subject to the effects of structural defects which occasionally cause irreversible damage. The use of soil as a construction material demands scrupulous respect of codes of good practice for the material and building systems. Structural defects may, however, be the result of causes which have nothing to do with the earth itself. These may include problems related to the site, e.g., settlement and earthslips, and natural disasters, which can have very serious effects on structures, particularly when they are poorly designed, badly built and carelessly maintained.

The principal causes of structural defects can be summarized as follows:

(a) Stresses on the material to which it is unsuited, such as tensile and bending stresses. Earth only functions well in compression. Other stresses require other materials: wood, concrete, and steel, (used as ties, lintels, etc.).

(b) Chronic damp, decreasing the strength of the material, even in compression.

(c) Construction on a poor site which cannot stand up to the loads transmitted to it, or on moving ground (slip, uneven settlement, heave and swell).

(d) Poor design of the building: under-designed or off-centre foundations, inadequately braced walls, untied walls, walls which are too high, walls with too many openings, or made of composite materials; excessive loads in the form of floors, roofs, occupancy and point loads; construction systems unsuited to the use of earth as a building material.

(e) Poor construction: poor quality material (e.g., unsuitable soil, poor bricks); poorly implemented construction techniques (e.g., mistakes in the bond, vertical cracking along joints); incorrectly mixed mortar; poorly designed openings, no ties, no protection at the top and bottom of walls (damp).

(f) Related causes: climatic influences (e.g., wind action on damp wall, loss of material); action of living organisms: plant parasites (mosses, lichens), rodents, insects (termites).

II. THE SUBSTRUCTURE

A. Foundations - basic rules

Unburnt soil structure with solid walls made up of smaller units such as bricks, adobes or compressed blocks, or monolithic walls made of cob or rammed earth can be approached along the same lines as conventional masonry.

Conventional foundation systems and materials are perfectly satisfactory. Foundations should be deep enough to be:

(a) Constructed on good soil. Be particularly wary for expanding soils or soils liable to severe subsidence (e.g., black cotton soils);

(b) Protected against the action of surface water and damp;

(c) Protected against frost;

(d) Protected from wind erosion which can wear away foundations (in severe storms);

(e) Protected against the effects of works in the vicinity (roads, gardening, agriculture);

(f) Protected from rodents and insects (e.g., termites).

Foundation blocks must be solid and be capable of providing effective transfer of loads to the soil without themselves being affected. To do this they must be made of strong materials.

Stabilized soil is not recommended and should only be used in exceptional circumstances on dry and well-drained sites. If it is the only possible solution, the foundations are built in stabilized rammed earth in an open trench, or in compressed blocks.

Stabilized earth foundations may be set on blinding concrete or on stoned pitching or a layer of sand. A coarse concrete or reinforced concrete slab in the bottom of the trench represents a considerable improvement.

In wet regions, soil foundations, even if stabilized, are out of the question. If there is no other alternative, steps must be taken to protect the surface or make it waterproof (coating with hard materials, waterproof skin, etc.).

All other conventionally adopted materials are suitable. Foundation slabs can be built in stone. In this case rubble can be used, laid as blockwork, over which a mortar is poured. They can also be coated with mortar and tightly packed against one another. Care must be taken to lay the rubble in a good bond to avoid cracking along the joints. This can be done by staggering the vertical joints.

The foundations can also be built in coarse concrete. The rubble is in this case embedded in the successive layers of concrete enveloping each layer of stones, covering these to a depth of at least 3 cm. The stones should not touch one another.

Burnt bricks are also suitable for making good quality foundation slabs. Good quality non-porous burnt bricks should be used, and care should be taken to construct the bond properly.

Finally, foundation slabs can be built using reinforced concrete and modern techniques.

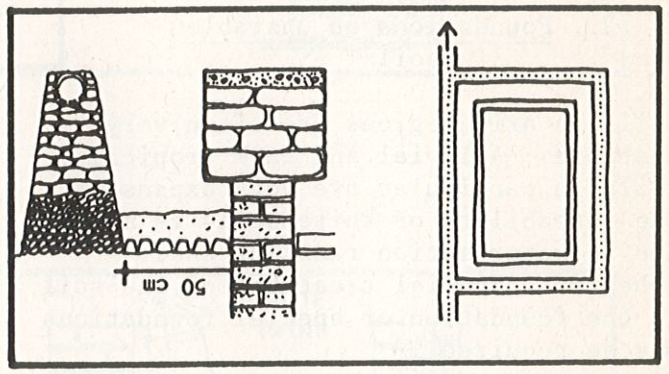
B. Foundations - Design details

1. Foundations for normal soil conditions

For normal soil conditions design of foundations should take the following into consideration.

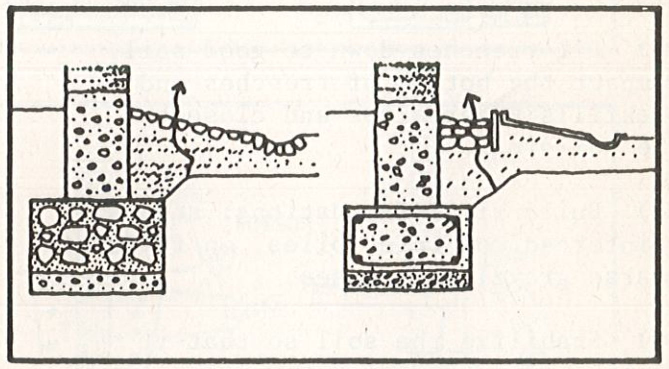
(a) Drainage

Good peripheral drainage is essential if water is to be kept away from the building. It must be constructed with the greatest of care to ensure its effectiveness. Drains should be built during excavations at the bottom of the trenches, close to the foundations or at a short distance (1.5 m) from the foundations. A channel (in burnt clay or some other suitable material) is laid at the bottom of the trench, which collects water and removes it by means of regular gradient. The drain is then filled with stones and gravel to create a filter system.



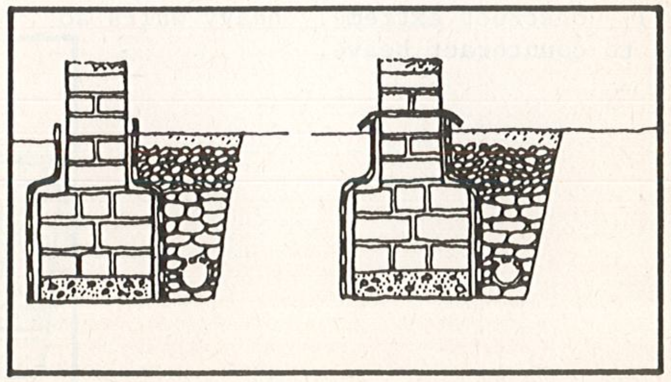
(b) Gradient and gutters

The soil outside the building is specially arranged. A gradient of 2 cm per m or more allows surface water to run off into a properly designed gutter some distance from the wall. Water-proofing the soil should be avoided (impervious pavement etc.) in order not to hinder the evaporation of moisture in the soil. It is better to spread gravel over a narrow strip. Trenches should be backfilled in compacted layers sloping towards the outside.



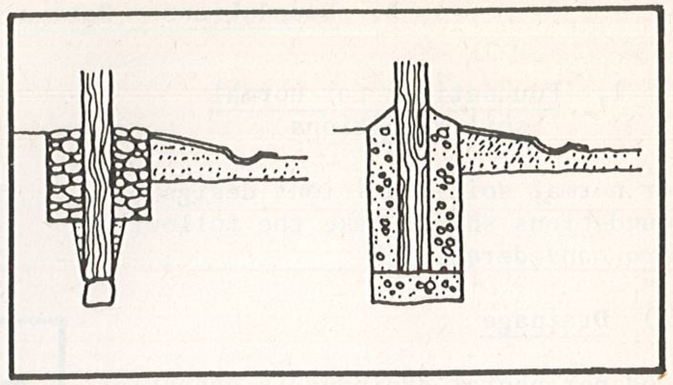
(c) Moisture barriers

These can be, among others, vertical screens on the outer surface of foundations or horizontal screens serving as an anti-capillary course between the foundations and the base course. Such moisture barriers must be perfectly continuous and may not be cracked or defective. A damp course can be made either of water repellent cement (500 kg/m^3) or a bituminous product.



(d) Wattle

Where daub or clay-straw is used, it is wise to take steps to treat the wood, particularly posts fixed in soil. Wooden posts should be embedded in the stone or concrete foundation slab. Care must be taken to drain around the structure.



2. Foundations on unstable soils

Soils in arid regions are often very unstable. Alluvial and dark tropical soils in particular are very expansive. The instability of these soils is mainly due to water action reducing their cohesion. Special treatment of the soil in the foundation or special foundations may be required.

For expansive soils:

(a) Keep water at a distance. A peripheral drainage is essential as well as a gradient sloping out-wards (at 5 cm per m) at the foot of the wall.

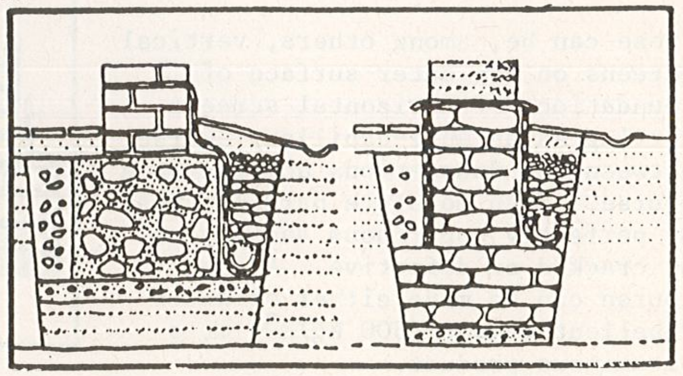
(b) Dig trenches down to good soil, compact the bottom of trenches and backfills under slabs and close to the building.

(c) Build rigid foundations: stones, reinforced concrete, piles, on fills of coarse gravel and stones.

(d) Stabilize the soil so that it will be less sensitive to water.

(e) Erect sufficiently flexible structures: wooden or metal frames.

(f) Construct extremely heavy walls so as to counteract heave.

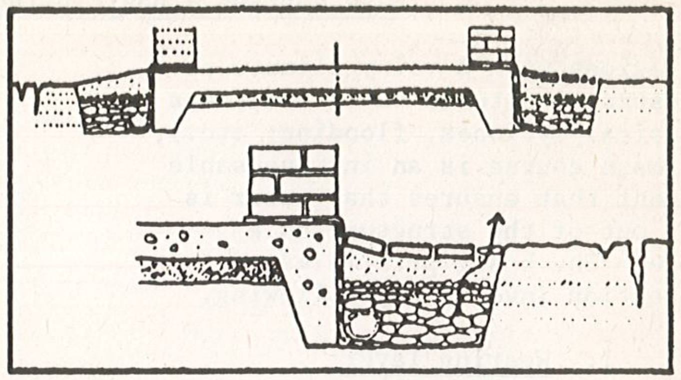


For soils lacking in cohesion:

(a) Provide for the escape of water and drain the edges. Do not hinder water evaporation.

(b) Ram the soil and/or stabilize. One method is to first flood the soil so that it is already packed once it has dried.

(c) Erect floating structures: floating slabs, sole plates. Stabilize the soil around the sides and under these floating structures.



3. Termite protection

Dampness and heat are favourable conditions for termite infestation. The following precautions should be taken:

(a) Combat dampness: drainage;

(b) Keep borders of the structure clean at all times;

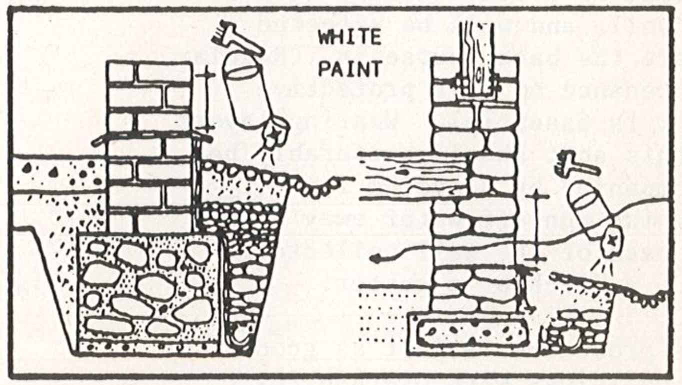
(c) Isolate the structural timber from the soil: build on studs or piles built in masonry. Treat wood: harden with fire, impregnate with old sump oil, or creasote;

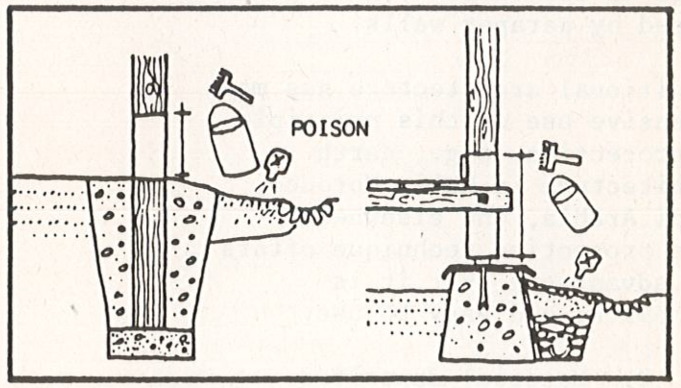
(d) Plug cracks in masonry;

(e) Paint the base courses white in order to make boreholes visible;

(f) Create a chemical barrier by treating the soil with antitermite insecticides;

(g) Stabilize foundations or base courses by incorporating crushed glass into the soil.





C. Base courses - basic principles

In regions with a rainy climate or exposure to natural water disasters (tropical cyclones, flooding, etc.), the base course is an indispensable element that ensures that water is kept out of the structure as a whole. The basic principles of protection involve the following.

1. Wearing layer

This basic technique is particularly suitable for soil base courses exposed to water erosion - e.g., splashing, condensation, etc. A solid layer of soil is applied to the base of the wall, and will be affected before the base course is. Regular maintenance of this protective layer is essential. Wearing layers of this sort should preferably be accompanied by a system for draining run-off water away from the base of the wall collected: e.g., a ditch or a gutter.

This procedure is just as good for buildings with overhanging roofs as for those with flat roofs topped by parapet walls.

Traditional architecture has made extensive use of this principle of protection, e.g., earth architecture in Mali, Morocco, Saudi Arabia, and elsewhere. This protection technique offers the advantages that it is economical and easy to use.

2. Material deposited at the base

Such protective materials as stones, bricks, wood, matting and tiles, among others are either deposited against the bottom of the wall or incorporated into its base. The thickness and height of the added protective material should be enough to allow good evaporation of pore water.

3. Construction of a base course

All known solid materials can be used: stone, brick, concrete.

The base course should be sufficiently high to cope with the constraints imposed by local eroding agents (water, wind), and follows the lie of the land and the layout of the surroundings: terraces, steps, etc. Care must be taken to provide a waterproof layer between the base course and the earth wall.

The height depends on local rainfall patterns, the likelihood of flooding, the overhang of the roof, and the evaporation of the water accumulated in the base of the wall.

- Dry regions: 0.25 m

- Average rainfall: 0.40 m

- Heavy rainfall, small roof overhang: 0.60 m or greater.

- Area susceptible to flooding (e.g., at the side of a watercourse): 0.80 - 1.00m, to allow a good evaporation of pore water absorbed by the base.

D. Base courses - design details

1. Stabilized brick

This material can only be used very infrequently, when it is certain that the site of the structure is dry, well drained and protected against infiltrating water.

The entire base course can be built in stabilized brick, observing the rules of sound construction (bond in particular) or only the facing. In the latter case the difference in strength between the stabilized and non-stabilized brick must not be too great.

It is recommended that this type of base course is finished with a rendering which allows the passage of water vapour. The rendering must end above the level of the ground if capillary absorption is to be avoided.

The edges of the structure must be laid out with care: slope away from the building, peripheral drainage belt, drainage ditch for surface water.

2. Burnt brick

Burnt bricks used for base courses should not be porous. If they are, the same precautions as for stabilized brick are adopted. In addition, burnt brick can also be used as a facing only or to make a protective coating of bricks and stones. This type of facing is an attractive solution for the repair of the lower part of a building being restored.

3. Stone

Depending on its permeability, stone is regarded as a more or less waterproof material. Good quality stones can be left visible, but care must be taken to rake out the joints so as to prevent water from infiltrating. Raking-out facilitates the bonding of any rendering.

4. Concrete or concrete elements

Concrete, when correctly mixed (250 kg/m^3) can be considered to be waterproof but it is advisable to protect it with a damp-proof membrane; particularly where it is buried or where the concrete is on the lean side.

Concrete blocks, whether solid or hollow, can be used for base courses but they are best for light earth walls made of straw-earth, for example. A damp-proof membrane screen is essential.

5. Stabilized rammed earth

Rammed earth can be stabilized throughout the entire thickness of the base course or on the surface alone. The second procedure has the advantage of being more economical but requires very careful execution. The non-stabilized and stabilized rammed earth are rammed simultaneously, layer after layer, the stabilized earth being rammed aginst the form on the outer facing of the wall.

A surface coating can also be applied down a vein of lime mortar in each compacted layer. The mortar is thrown with a trowel and its thickness controlled by a mark on the formwork to ensure good finishing of the wall.

6. Cladding

Cladding (slabs of wood or shingles, nailed onto laths) can be fitted against the base course. This type of work often requires a wooden lattice to carry the cladding. An air space increases the effectiveness of the system by permitting ventilation and evaporation of moisture which might be retained behind the cladding.

Woven reeds and straw matting make cheap cladding but must be regularly maintained and periodically replaced. Cladding has the added advantage of offering thermal protection, particularly when ventilated.

7. Surround, footway

This can be a simple timber positioned lengthwise in front of the base course, immediately below the roof gutter to catch any drips. Bottles, tin cans or stones driven into the earth are just as satisfactory.

Upended posts, held by cross pieces and retaining an earth pavement form a more elaborate system. The pavement should have a slight gradient and be provided with a drainage ditch.

8. Encrusted renderings

A rendering covering the base course and encrusted with gravel or stone chippings, constitutes a good wearing layer.

9. Temporary protection

During the rainy season simple tiles or flat stones positioned against the base of the wall form satisfactory and extremely cheap protection.

III. WALLS

A. Walls - basic principles

Building experience has established an empirical relationship for earth brick walls, where the thickness of walls should be at least 1/10th of their height. The minimum thickness of rammed earth walls in single storey structures should be taken as 30 cm, while with a floor it should be 45 cm. Similarly the distance between partition walls or buttresses or expansion joints (dry joints planned in advance or kept strictly away from openings) should not exceed 5 to 6 m.

Earth walls made of adobes or compressed blocks must satisfy the same requirements with regard to bond as brick or stone walls. Walls must be protected with particular attention to the prevention of capillary rise at the base, condensation of vapour on cold walls, and humid rooms, as well as rain, frost and snow. Earth walls or parts of walls exposed to erosion due to wear - bottoms of walls, corners, tops of walls, parapets, reveals in openings, etc., - must be protected by a rendering or "hard" masonry work. Surface hardening occurs with a risk of smouldering where wood is incorporated in the structure (ties, for example).

The mortar used for joints should have the same compression strength and erosion resistance as the bricks. If the strength of the mortar is less, erosion and infiltration of water will occur and bricks will deteriorate. If the strength of the mortar is greater than that of the bricks, the bricks will erode, water will stand on the exposed surface of the mortar, and aggravate the erosion of the bricks.

The mortar should be checked in prior tests for shrink, adhesion, erosion and compressive strength.

Stabilized mortar must be used for stabilized bricks. If the texture and water content of the mortar is different from those of the brick: the proportion of cement or lime in the mortar must be increased from 1.5 to 2 times in order to achieve the same resistance as the stabilized brick.

The shrink of the joints causes a horizontal shrink of the wall of from 1 to 2 mm per 5 m. The settling of the joints under the load causes a vertical shrink of the wall from 1 to 2 cm per 3 m.

In principle, good construction practice should give consideration to:

(a) Texture of the mortar: sandier than that of brick with a maximum grain size of 5 mm, but preferably from 2 to 3 mm;

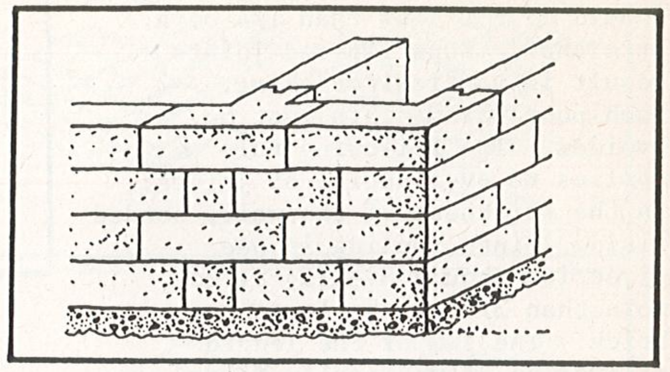
(b) Thickness of joints: horizontal and cross joints should have a maximum thickness of 1 to 1.5 cm, with a maximum tolerance of 2 cm for adobes;

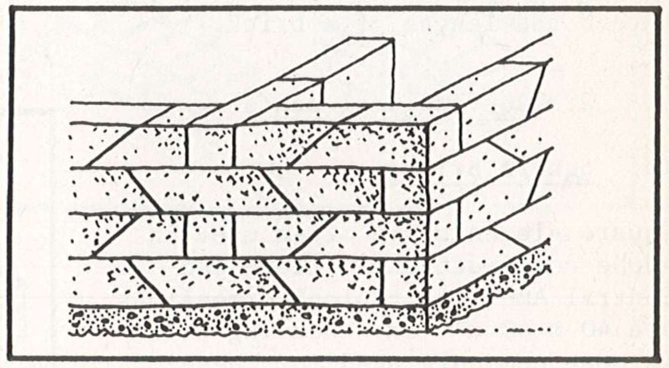
(c) Execution: stabilized bricks must be pre-soaked and the bed thoroughly wetted. Mortar must be spread over the joint faces of the brick and the right quantity must be used. The brick is laid down rather than tapped. Protection against the sun and wind is recommended;

(d) Jointing: immediately after laying, rake out to a depth of 2 to 3 cm, joint up flush with mortar, and firm with a jointing tool.

B. Brickwork

1. General rules





The bond of adobe and compressed block walls must be carefully worked out (position of the joints). A poor bond can cause structural faults: e.g., vertical cracking. The rules which apply to plain brickwork are the same as those for burnt brick. Rammed earth moulded in adjustable forms should be treated as masonry with a large bond, where the cross joint must be staggered at least 1/4 of the length of the form and provided with perfect toothing at corners and wall joints. The dimensions of the forms must accordingly be adapted to the bond planned in the design of the project in relation to the extreme dimensions of the design. The joints can be straight (Morocco, Peru, for example) or inclined at an angle (France, for example) and, if possible, grooved for better bonding.

Bricks or earth blocks have 6 surfaces: a top and a botoom, two ends and two edges. The bonds in which the bricks are laid are named after the places where they are widespread and the pattern they make on the surface of the brickwork.

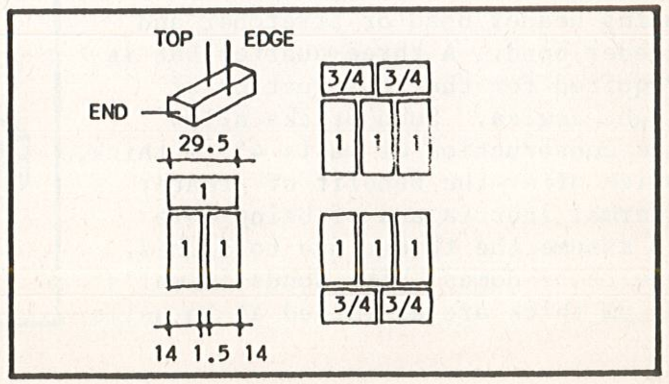
Headed bond: the brick is set in such a way that its greatest dimension is contained in the thickness of the wall, one of its ends appears on the surface.

Stretcher bond: the greatest dimension and one edge are visible.

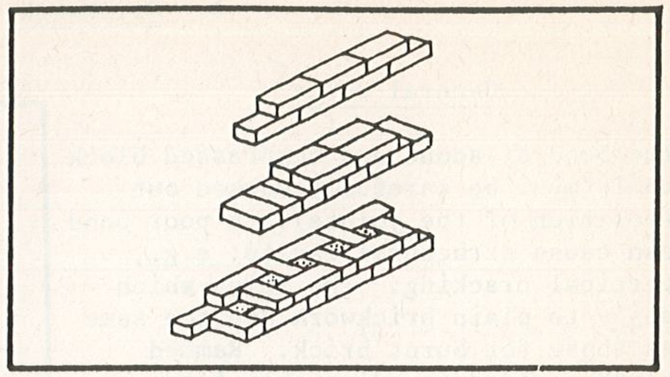
Tile bond: the greatest dimension and one face are visible - to be avoided since the brick is set in the cleavage plane.

Heading bond: the two ends of the brick are visible on both surfaces of the wall.

Modulated bond: brick walls are usually laid using complete bricks, but three-quarter bats, and half-bats are also used. The bonds in pillars often use three-quarter bats.



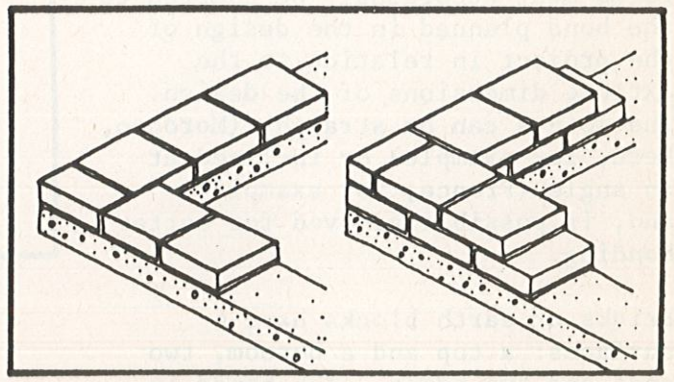
The distance between two cross joints on the surface of the wall, from one course to another, should be not less than 1/4 of a stretcher. Superimposed joints result in vertical cracking. Such poor workmanship must be avoided. The following rule applies to overlapping of joints: In the thickness of the wall, bonded rising joints running in one direction should overlap by no more than 3/4 of the length of a brick. The sum of the length of overlap of vertically bonded through joints should not exceed the length of a brick.



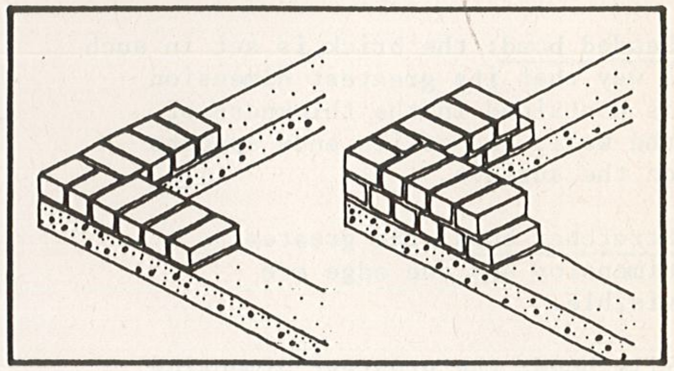
2. Conventional bonds

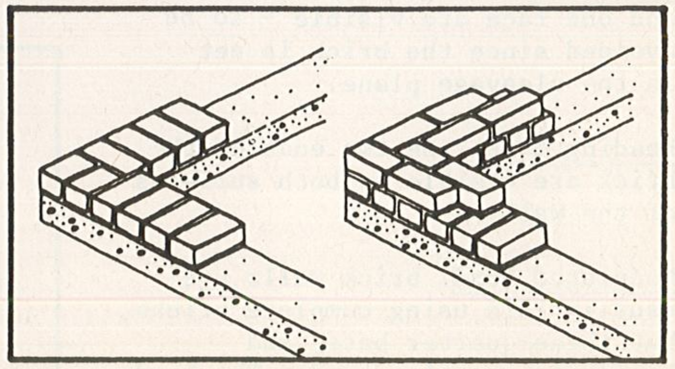
(a) Square bricks

Square elements are often used in adobe construction in South and Central America: typical dimensions are 40 x 40 x 9 cm. Heading bond is most commonly used for these adobes. The corners require the use of a 1/2 bat for good toothing; a bigger, rectangular brick helps to prevent weakening of the corner. The same applies to the bonding of outer and partition walls.

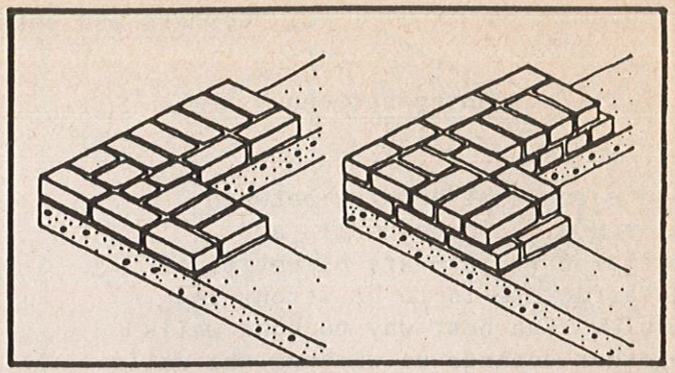


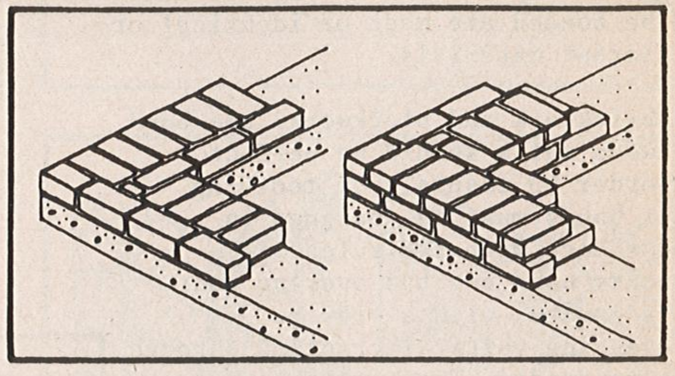
(b) Rectangular bricks





The most commonly used rectangular element, produced by the great majority of presses on the market, has nominal dimensions of 29.5 x 14 x 9 cm. Variations in the thickness of the block do not affect the bond in the chosen beding plane. This type of brick allows the construction of thin walls only 14 cm thick in stretcher bond, and walls 29.5 cm thick using header bond or stretcher and header bond. A three-quarter bat is required for the construction of right angles. Such bricks allow the construction of walls 45 cm thick, which offer the benefit of greater thermal inertia and of being able to assume the thrust due to arches, vaults or domes. The bonds in walls 45 cm thick are as varied as in walls which are not so thick. Walls may be header and stretcher bond where 3/4 and 1/2 bats are used for the corners or in headers or stretchers, using 3/4 and 1/4 bats for the corners.





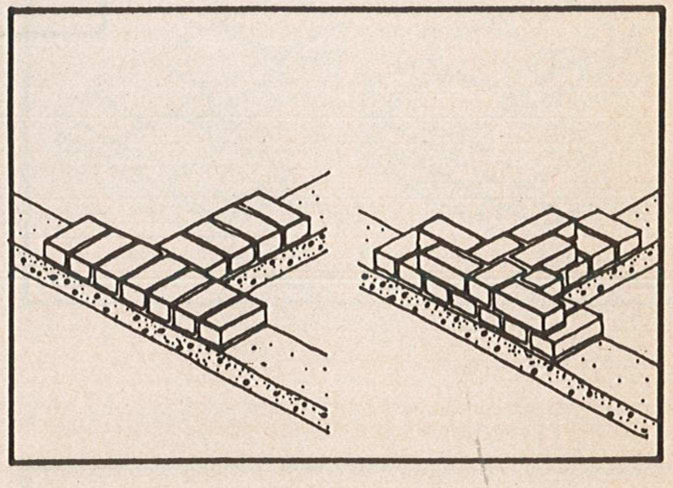
Thicker walls - e.g., 60 cm - require the use of 3/4, 1/2 and 1/4 bricks for corners and joints between walls. Very thick walls, in view of their greater complexity, are more difficult to execute, and are less economical because of the greater quantity of materials used and lower speed of laying the brick. Other construction methods should be sought for thicker walls in plain earth, such as rammed earth or cob.

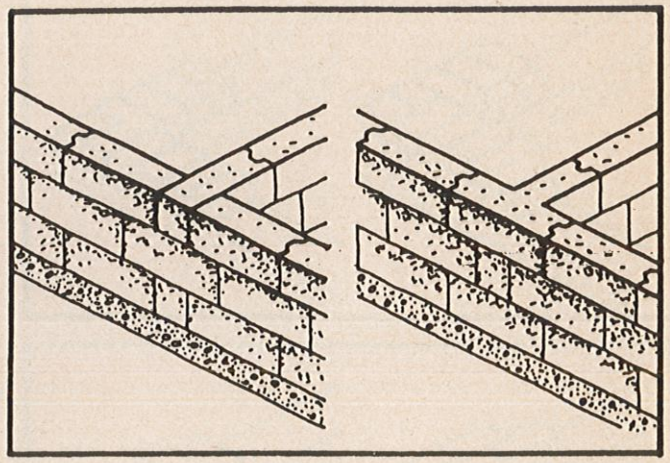
C. Corners and partitions

1. Bonding between walls

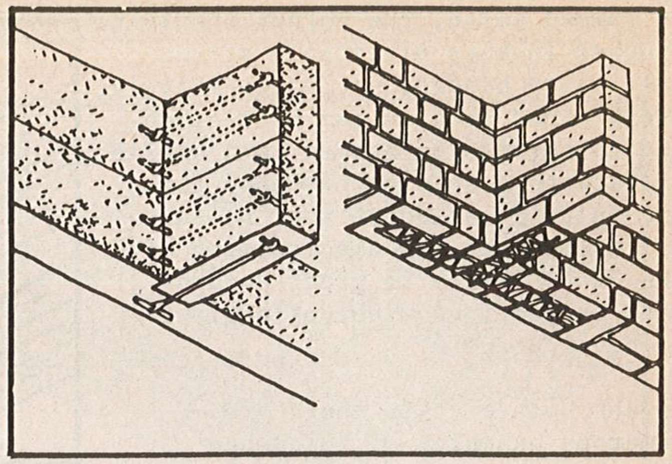
Good structural bonding between walls - e.g., outer walls and partition walls - are essential if the structure is to be strong and stable. The best way to bond walls together depends on whether the walls to be bonded are made of identical or different materials.

In brickwork and blockwork, the bond between walls should be perfect, in order to ensure good toothing Wall bonds must be designed in accordance with the rules of masonry bond and the overlap must be adequate, with a view to preventing vertical cracking through the perpends. The complexity of the bond between walls depends on their thickness, and the use of 3/4 bats and 1/2 bats is fairly common. Where a thick wall and a thin wall are to be bonded a vertical groove in the thick wall can be provided into which the thin wall can be fitted. Horizontal strengthing must, however, also be provided (bars, wood, netting). These strengthen the "T" bond between the walls, which may be installed every fifth or sixth course of bricks. Ties should also be constructed to link walls continuously at floor level. In rammed earth construction the wall bond can be rammed in one piece by means of a special "T" form, or the sections can be toothed in two directions: one section in two of the partition wall extending into the outside wall. A slot in the outer wall can also be provided, but in that case the wall bond must be strengthened horizontally in all directions and for all sections.



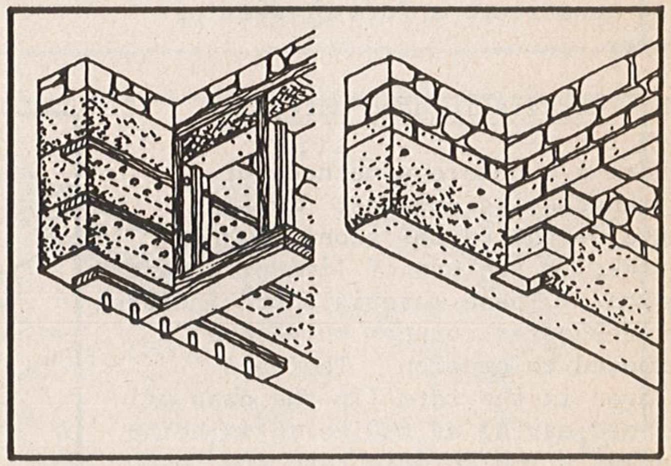


In cases where different materials are used toothed wall bonds are not recommended since the difference in function and strength of the materials could cause cracking. The best procedure is thus to make a slot in the thicker wall. For bonding light wooden frame dividing walls to rammed earth walls the best course is to embed boards in the rammed earth and to screw the dividing wall to the boards. The last wooden post for the partition can also be sunk into the wall.



2. Corners

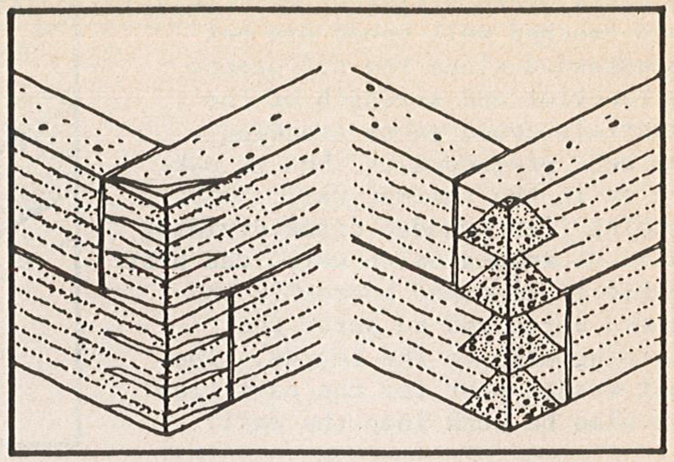
The stability of the corners is largely responsible for the stability of the structure. It is usually in the corners of earth houses that structural cracks which jeopardize the structure can be observed. These cracks may be caused by the different rates of settlement of the gound and the structure (in the case of poor foundations) and it is thus the corners which suffer most as well as the other wall bonds. Such fissures, however, may also be the result of poor bonding between the walls.



(a) Corners in earth

In adobe or compressed block masonry, the construction of corners requires the strict application of the rules of the bond. Furthermore, breaking bricks into smaller parts must be avoided so as not to weaken the corner. If at all possible, a 3/4 bat is the smallest element which should be used. A 1/2 bat is acceptable if necessary, but a 1/4 bat is too small.

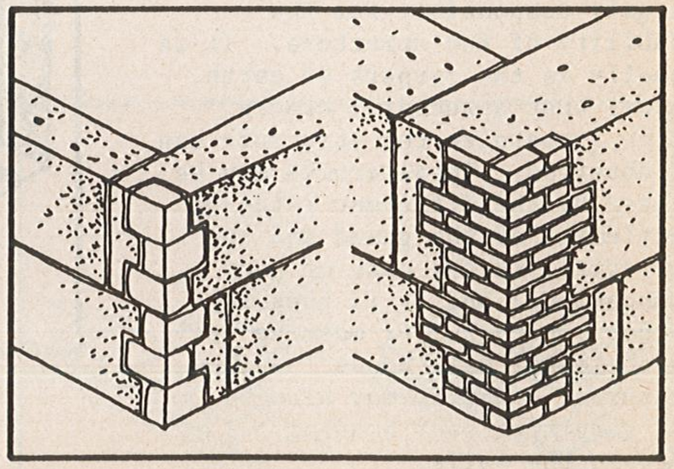
In rammed earth, the corner should be touched in both directions of the wall being bonded, or, alternatively, every other section can be toothed. The corner can be formed in a single piece with a special L-shaped form, and in this case care must be taken to ensure that the displacement of the cross joints is great enough between sections. Do not neglect to bevel corners.

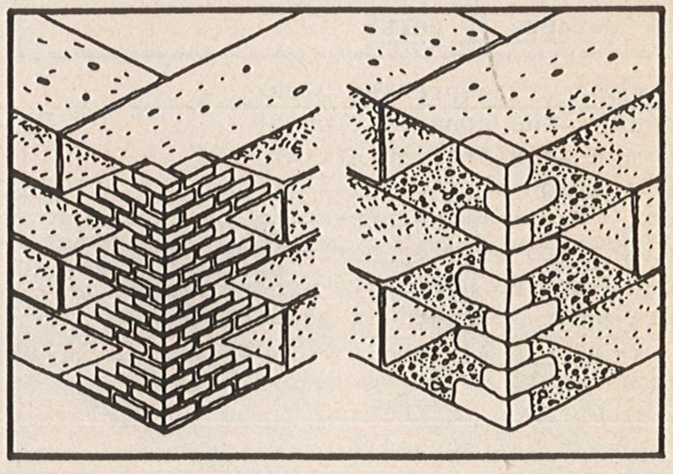


In cob construction there are numerous examples of thickened corners. These are very acceptable and constitute a form of wearing layer.

(b) Corners in hard materials

There are numerous methods of strengthening corners. These involve the use of stone, burnt brick, or the use of lime or cement mortar. These materials are included in the outer corners which are exposed to erosion. They are placed in the form (in the case of rammed earth) as the earth is being rammed. The corners take the form of rectangular or triangular toothing to ensure good bonding between the "hard" material and the soil. A layer of mortar between the two materials enhances their bonding. The strengthening of corners with layers of mortar must be carried out carefully and uniformly.

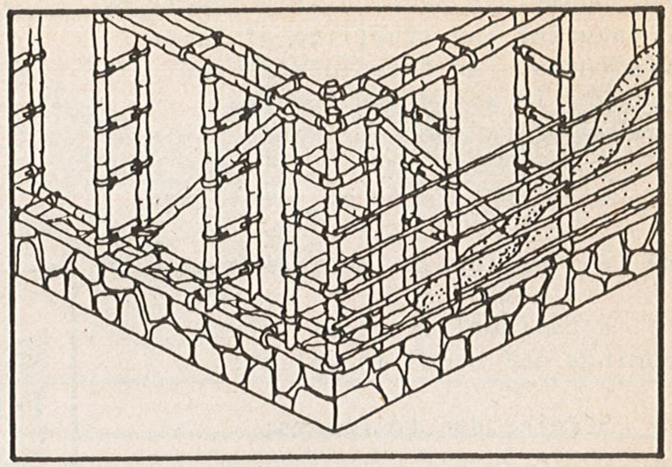




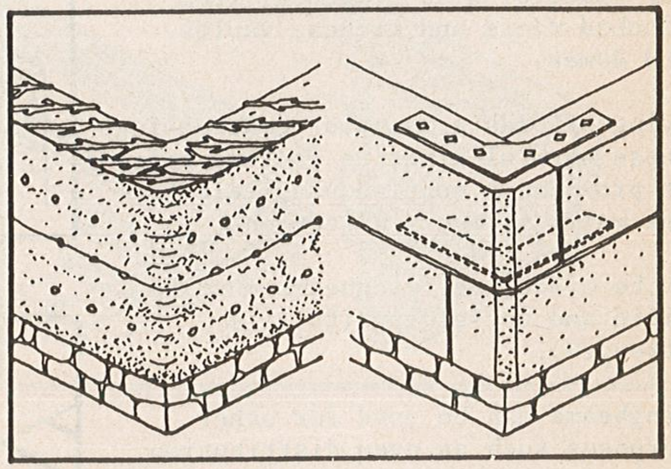
D. Reinforcements and bondbeams

1. Strengthened walls

To cope with stresses other than compressive stress, builders have developed methods of reinforcing walls. Particularly well-known are the techniques which use studding, daubed wattle, clay-straw infills together with wooden frames or structures which form an integral part of the walls.

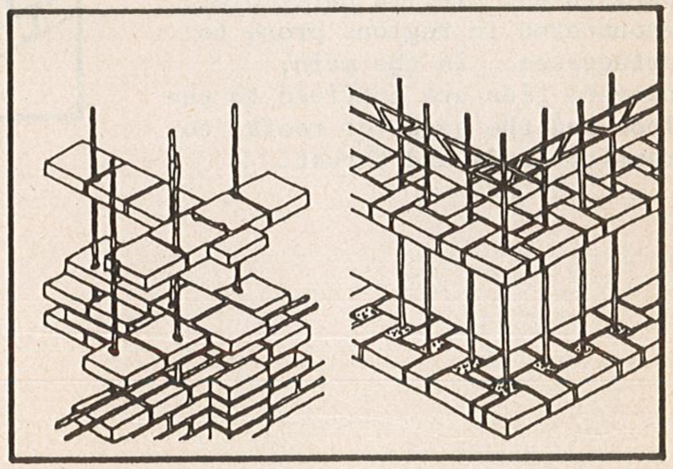


Horizontal and vertical ties are the most frequently used reinforcement systems. These are sometimes localized and positioned in the weakest parts of the walls, such as corners, or reveals of openings. They are made of wood or iron (e.g., sills) metal lattice work or netting (in corners).



A rendering on wire-netting serves as a reinforced "skin" which must not be used to conceal structural defects, such as vertical cracking. If it is used for such a purpose, it could prove ineffective. Earth rammed in gabions is also used to reinforce walls.

For thin walls (29.5 x 14 x 9 cm bricks in stretcher bond), the use of buttresses integrated into facades around door and window openings can be considered (simple abutment outwards). The walls are also tied horizontally at floor or roof level. For gable ends, a pillar should be integrated in the axis of wall, worked into the bond and properly toothed into the wall. This pillar stiffens the wall, provides better resistance to wind loading and takes up the load of the ridgepole. Ties at the base of the gable transmit the thrust from the roof.



2. Ring beams

Ring-beams are particularly important in ensuring the stability of earth structures. In fact, cracks and breaches in walls are due in particular to the following:

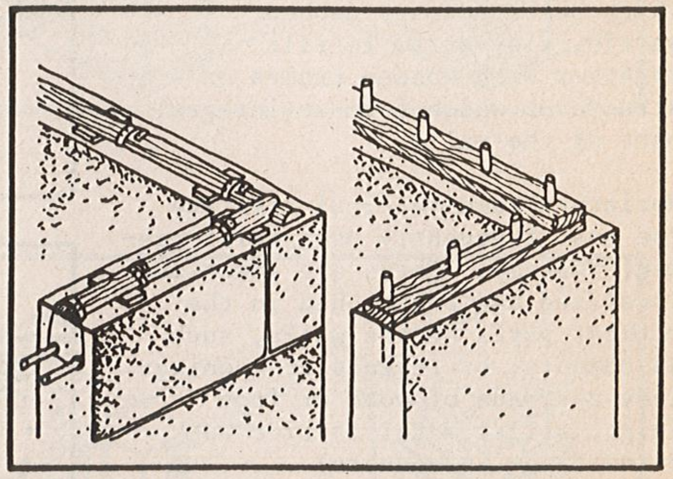
(a) Different rates of settlement;

(b) Shrink, swell, thermal expansion;

(c) Rotational or shear stress (e.g., openings and bonds in walls);

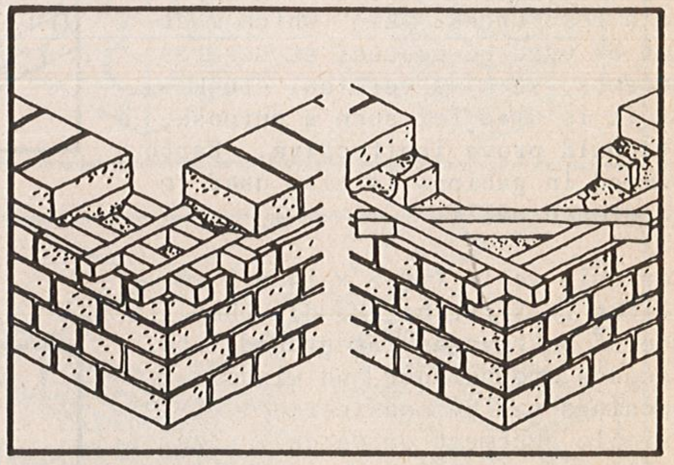
(d) Strains due to floors;

(e) Lateral wind pressure, from pitched roofs and arches, vaults and domes.



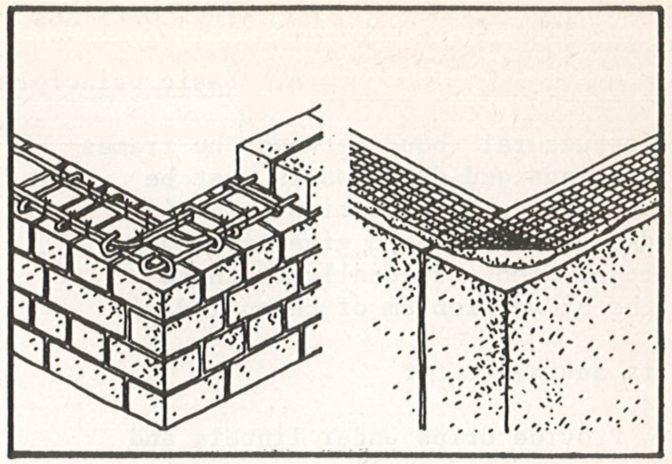
Tying affords a means of controlling these harmful limiting factors since it provides a continuous girdle for the walls in every direction.

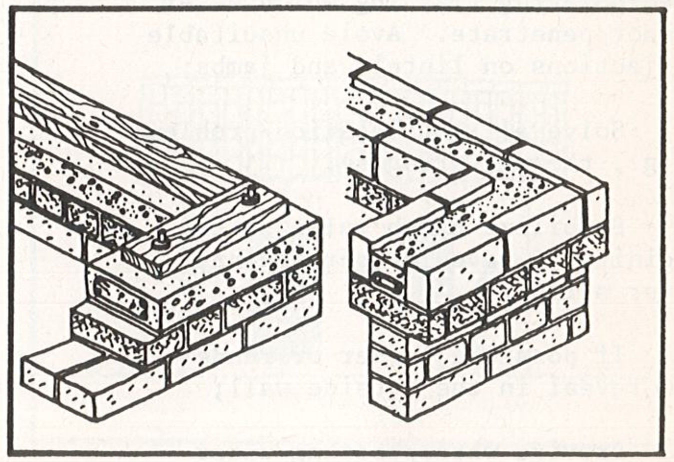
To be effective, ringbeams must be rigid and unyielding (tensile strength).



Ringbeams can be used for other purposes such as even distribution of loads, wind-bracing, continuous lintel, support and anchorage of floors and the roof. Intermediate tie systems also exist. These are used in the sills and lintels of openings and are, in particular, encountered in regions prone to earthquakes. In the main, however, ties are confined to the floor and the edges of roofs, to transfer loads and thrust.

The main materials used are wood, steel and concrete. These materials must have a high degree of adhesion with the soil in order to ensure the effectiveness of the tie. Wooden ringbeams are often set in the thickness of walls, after immersion in mortar or anchored by means of steel or metal collars. Economic and quite effective solutions consist of using local wood such as bamboo or eucalyptus. Wood is prone to water and fire damage and damage by termites if it is not specially treated. It is desirable to use treated and dry wood from which the bark has been stripped.





Steel ties must be fastened properly, especially at the angles of walls and adequately coated with mortar and concrete. Metal lattice ties also exist. It is advisable to cast the tie in reinforced concrete upon a layer of stabilized earth in order to ensure that the concrete adheres well to the earth and that there is no deterioration due to contact with wet material.

IV. OPENINGS

A. Basic principles

The structural bond between the frames of openings and earth walls must be given particular attention to avoid cracking, which would give rise to rapid erosion, especially if there is the added problem of chronic damp.

It is advisable to:

(a) Provide drips under lintels and sills, on outside walls, or a system incorporating flashing which water cannot penetrate. Avoid unsuitable projections on lintels and jambs;

(b) Solve all condensation problems (e.g., thermal bridges);

(c) Stabilize earth walls in the vicinity of reveals (particularly under sills);

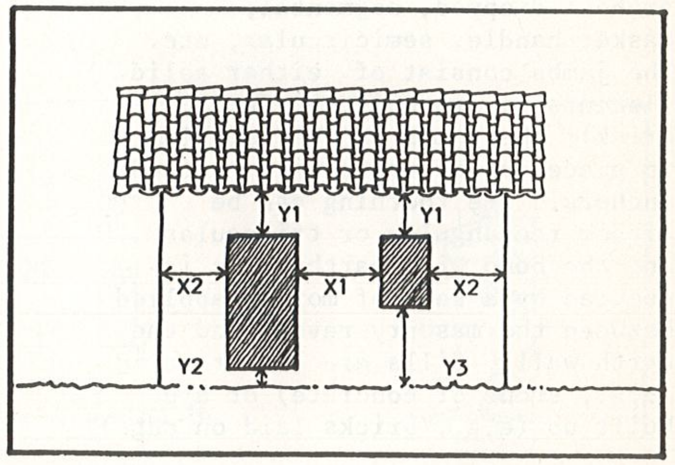
(d) If possible, cover or render the reveal in the outside wall;

(e) Provide waterproofing under sills.

The reveals of openings should be generously designed: heavy lintels and sills and stable jambs are required. Point loads must be taken up. The openings can be dressed in wood or masonry (taking care not to increase differential stresses between the frame and the wall). The opening can be cut after the wall is dry, but the lintel must be fitted beforehand.

Lintels can be made of wood or concrete, stone, or brick. It can be cast in situ or prefabricated. Lintels are subject to considerable stress. The lintel must be supported in the wall over at least 25 cm, and more for large openings. It is moreover advisable to increase the compressive strength of supporting lintels: stabilize jambs or dress them in a masonry. In designing sills, loads transmitted by the jambs must be properly taken up. Lengthen the sill and add reinforcement under the sill. To prevent shearing of the window breast, it is best to use dry joints between the breast-wall and the wall proper or else use independent infilling after the construction of the wall: e.g., rammed earth wall, sun-dried brick breast-wall. Plug the dry joints of the breast-wall once the wall has completely dried and is stable.

The following rules are vernacular guidelines, and do not exclude variations in the design of openings.



(a) The ratio of apertures to solid sections in any one wall should not be greater than 1:3 and should be as evenly distributed as possible. Avoid concentrations of apertures or excessively large openings.

(b) The total length of the openings should not be more than 35 per cent of the length of the wall.

(c) Conventional spans should not exceed 1.20 m.

(d) The minimum distance between an opening and a corner is 1 m.

(e) The width of a pier should not be less than the thickness of the wall with a minimum of 65 cm. Piers less than 1 m wide cannot bear loads.

(f) The ratio of the height of the breast-walling under sills and above lintels to the width of the bay should be adequate.

B. Basic details

The reveals of openings can be dressed with "hard" materials so as to ensure that loads and stresses are properly taken up. This procedure facilitates the anchoring or fixing of joinery, but the provision of such hardening is difficult: problem of the bond between "hard" materials and earth walls.

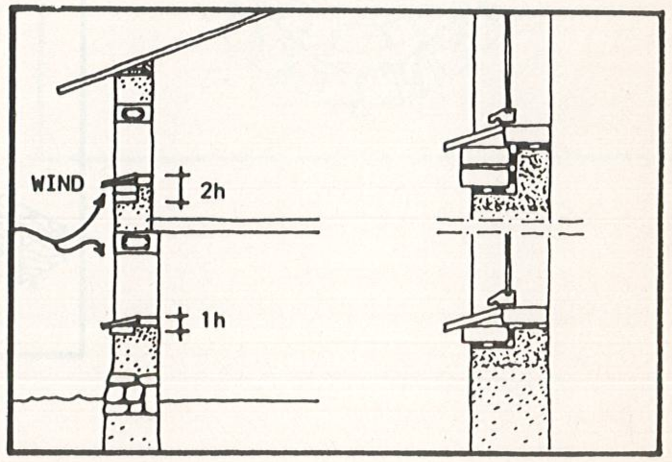
Stone or brick lintels can be in the form of straight lintels or a lintel course, or variously shaped arches: dropped, segmental, basket-handle, semicircular, etc. The jambs consist of either solid elements or are built up (e.g., brick); the jambs can be secured in place in the walls with toothed anchors. The toothing can be either rectangular or triangular and the bond with earth walls is secured by a seam of mortar applied between the masonry reveal and the earth wall. Sills are either solid (e.g., stone or concrete) or are built up (e.g., bricks laid on edge).

Concrete makes it possible to build monolithic reveals, cast while the earth walls are being erected or prefabricated. The bond between the concrete and the earth (toothing) must be good and projections of concrete with respect to the bare earth wall should be avoided.

Wooden reveals are very widespread. The lintels, jambs, and sills constitute a rigid frame. This can either be set on the outside of the wall or form a solid mass extending through the entire thickness of the wall. Adequate penetration of the lintel or sill through the earth wall ensures good structural bonding of the materials. Nevertheless, it is advisable to place boards on a mortar bed or even on brickwork. In regions with a damp climate it is better to render these wooden frames (roughing or studding of wood) and provide flashing above the lintel.

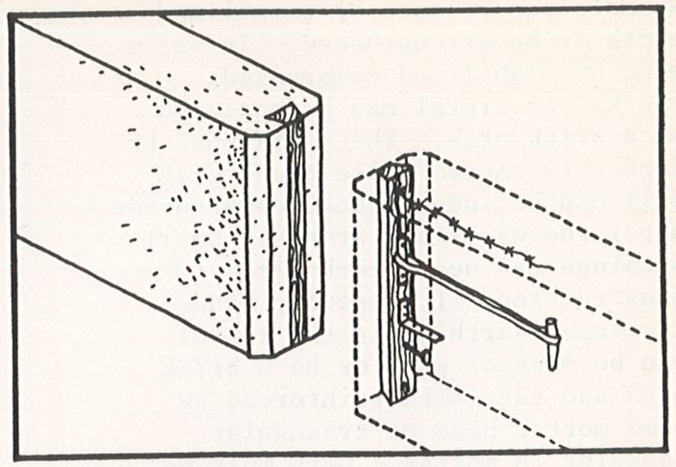
Reveals can be made of stabilized earth or be strengthened. In walls made of stabilized compressed blocks the lintel can be replaced by a brick arch. The jambs must be perfectly bonded while the breast wall can be independent, constructed after the walls and arches. Small openings can be of corbelled construction, if carefully bonded. In rammed earth walls the lintel can be made of wood or be a brick arch and the jambs reinforced by lime mortar beds or triangular toothing in mortar. Care must be taken to bevel projecting angles so as to reduce erosion.

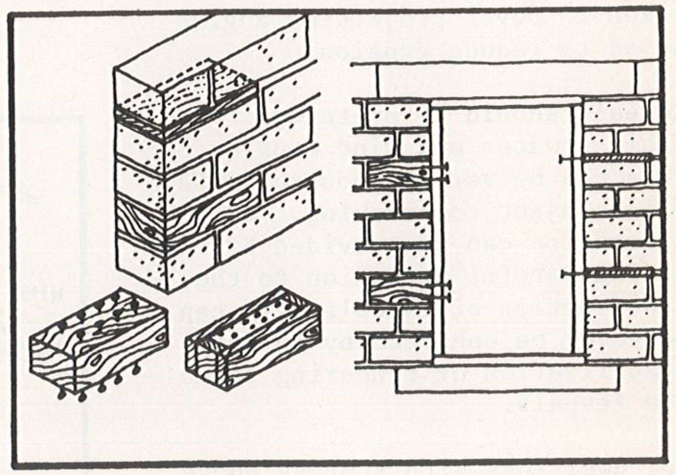
Reveals should be protected against water and wind erosion. This can be very pronounced on a wall subject to cracking. Such protection can be provided by giving careful attention to the construction of reveals. It can moreover be enhanced by surface stabilization or rendering round the reveals.



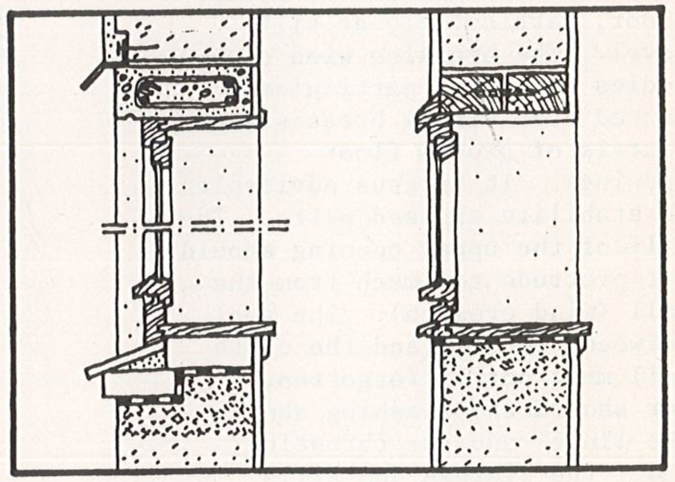
For dwellings with storeys above ground level, openings on walls facing the prevailing winds are more exposed than on the ground floor, particularly at sill level. The breaking wind creates eddies which are particularly marked near window breasts and lintels of ground floor openings. It is thus advisable to stabilize exposed parts. The sill of the upper opening should not protrude too much from the wall (wind erosion). The seal between the sill and the earth wall must not be forgotten, nor should the flashing above the lintel and the throating under the lintels and sills be neglected.

When it is planned to fix subframes, for windows and doors directly in earth walls care must be taken to provide solid anchoring as the shocks and vibration resulting from frequent use can cause cracking and loosening. Pieces of wood, to which the joinery can be attached, can be embedded into the earth walls. The fastening of these boards (planks in the form of jambs or special blocks) is done by means of metal holdfasts, by nailing and setting after coating in mortar, or by means of barbed wire ties which are progressively sunk into the wall as the jambs are built.





The joinery should be made with great care and should be provided with throating on the underside if it projects beyond the wall. If the joinery is recessed, the sill must be provided with a weathered surface and be well inclined so that the water can be drained away. Care must be taken to fix shutter hinges securely in the wall. The damp-proofing under the sill must not be forgotten.



C. Arches

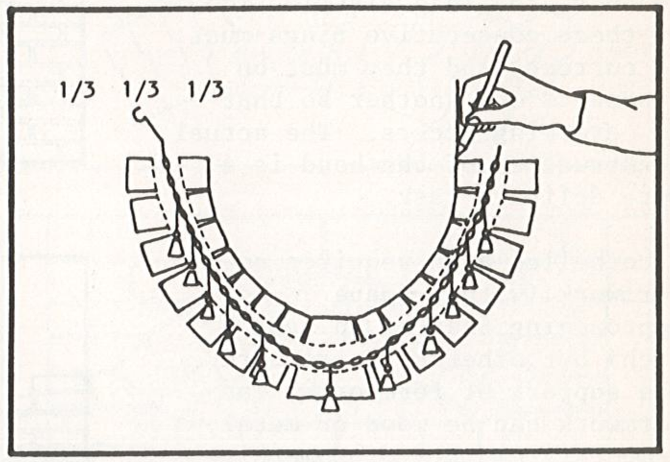
1. Arch design

The lines of thrust within the arch can be evaluated by various methods: calculation, graphically, or by simulation.

There are two main solutions to the problem of arch design:

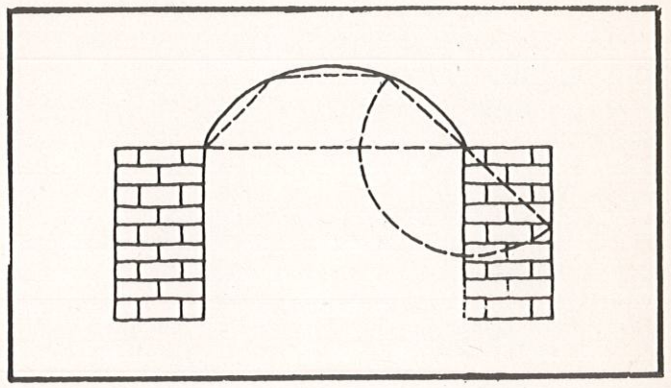
(a) The shape of the arch is determined in advance. The plot of the thrust lines should pass within the middle third of the arc and the arch is given the required thickness.

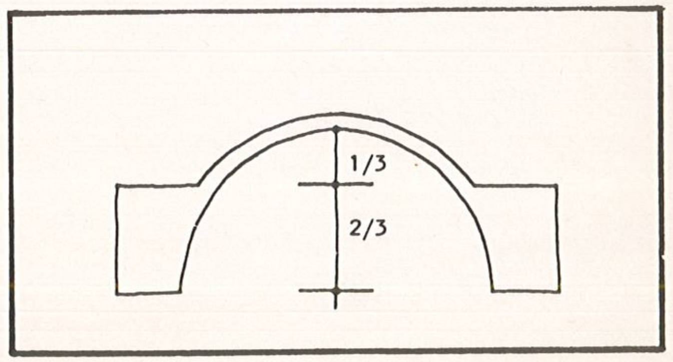
(b) The thrust lines are determined and the shape and thickness of the arch adapted to them.



Even so, the calculations do not exactly reflect reality as the masonry loading the arch is not passive. It has its own internal cohesion and forms a corbelled arch (this can be observed in walls which have collapsed, and the span may be as much as 7 m). Any plot of thrust lines is therefore hypothetical. It is thus essential, especially for large spans, to build the araches with great care to avoid cracking and loosening.

Arches transmit great thrust onto the springing points and onto the piers supporting these. Consequently, the latter must be solid and stable. These thrusts can be calculated or estimated graphically (e.g., the Maxwell-Cremona polygon of forces). It is also possible to estimate the size of piers by an empirical method: the prolongation of the first third if the arch should always fail within the pier. When two arches having the same plot meet on the same pier, the thrusts cancel one another out. In this case, only the descending vertical load is considered.

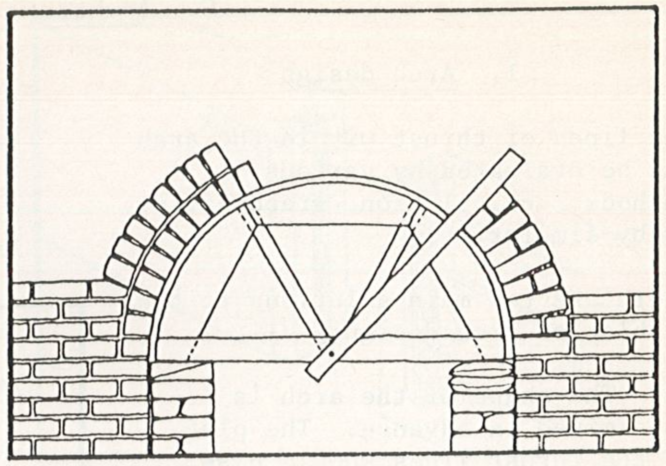


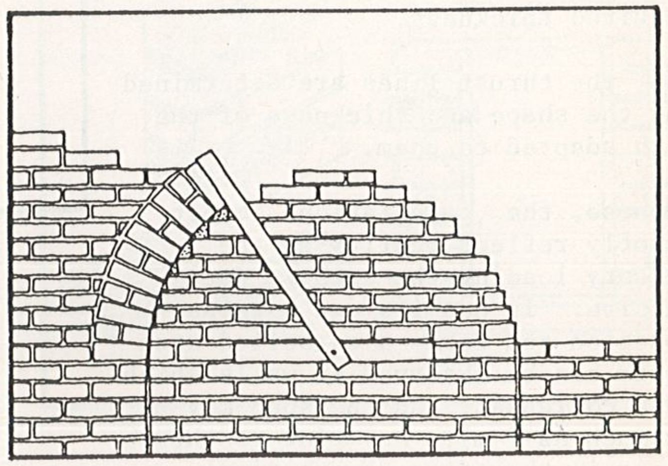


2. Building arches

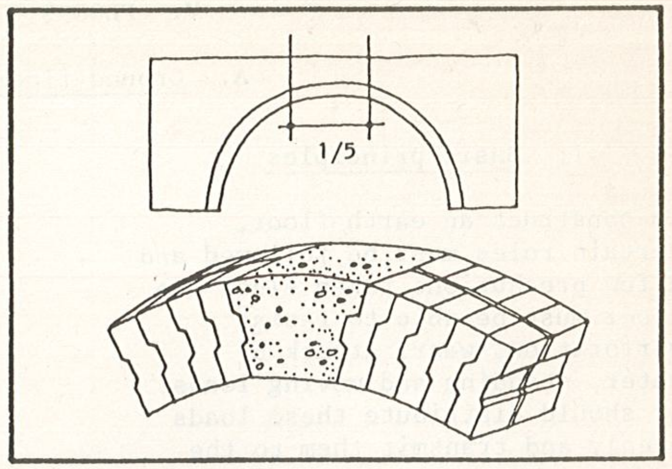
Depending on the span and loads involved, arches may be built using a single, double or triple ring. A light formwork permits the construction of the first ring, which serves in turn as a base for the second, and so on. However, the load distribution of these consecutive rings must be correct, and they must be bonded to one another so that no cracking occurs. The actual construction of the bond is a more delicate task.

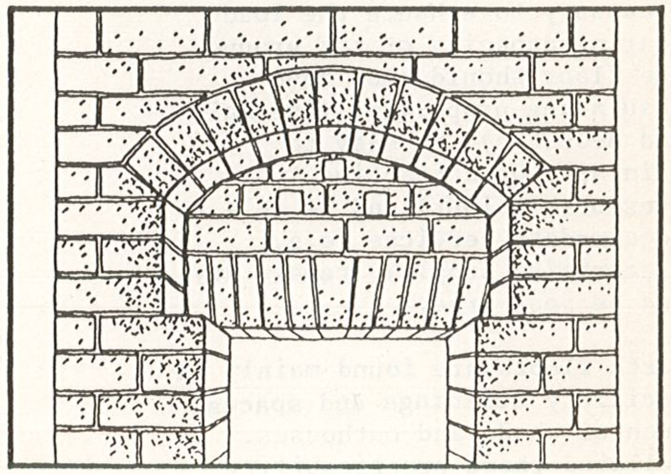
A corbelled arch requires no formwork (with a shape approaching that of an ogee arch) but other sorts require the support of formwork. The formwork can be wood or metal, temporary masonry or something even lighter (e.g., formwork made from palm trunks with a coat of rendering). The use of wedged wooden blocks or small sandbags, allows the formwork to be removed without stressing the arch (risk of cracking).





Arches made of adobes or stabilized compressed blocks must be well bonded: the heads of the joints between the masonry and the arch must correspond. Construction proceeds symmetrically from the two imposts of the arch and ending with the keystone. The imposts are recessed in the wall and are cut so as to determine the direction of the arch and to take up the thrust as well as possible. In principle the mortar is not taken into account when constructing the arch, the bricks are regarded as if they were laid dry. The bricks touch at the intrados, on the formwork and are wedged at the extrados by a pebble. The packing of the joints must be carried out with great care. Special voussoirs can be used (trapezoidal or interlocking) which prevent slipping. These bricks are better suited to large spans, and the arch and the masonry which it bears are constructed simulteneously. In large arches the keystone is ideally made of a material which is cut to size on the spot and will be quite wide (40 cm). When pebbles are used for wedging, the formwork can be removed immediately. If only mortar is used, it is necessary to allow a drying period before daring to remove the forms.





V. FLOORS

A. Ground floors

1. Basic principles

To construct an earth floor, certain rules must be followed and a few precautions taken since the floor must be able to resist perforation, wear, attack by water, standing and moving loads. It should distribute these loads evenly and transmit them to the ground. Furthermore, it may be necessary to enhance the load-bearing capacity of the ground. The floor should also have insulating properties (thermal and acoustic), be easy to maintain, be attractive (texture, colour) and be able to accommodate services (e.g., electricity supply), remain dry and be pest-free.

Earth floors are found mainly in ancillary buildings and spaces such as sheds and outhouses. In cellars, their practicability depends on the permeability of the underlying ground and the level of the groundwater (at least 3 m) and how well the cellar is ventilated. In general, earth floors can be used for dry and well-ventilated spaces, on well-drained and dry soil. They are also used for living areas (e.g., living-room, bedrooms), but this demands very careful finishing and a more elaborate design (e.g., insulation). Their strength, going up to 350 daN/cm^2 for point loads, is high.

Floors and walls function differently, walls can support heavier loads than those applied to floor slabs. Consequently the floor should be made structurally independent of the walls so as to avoid cracking due to different rates of settlement. The material of the damp-proof membrance against the foundation slab must be flexible so as not to be altered by the different stresses applied by the two structures. The preparation of the underlying soil upon which the earth floor is constructed must be painstaking so as to avoid settlement. Levelling, back filling if necessary, and compaction are the required means.

The thickness varies depending on the load-bearing capacity of the underlying ground, the stresses due to the applied loads and the chosen finish. A floor comprising a foundation in pitching, a sand profile and covered by rammed earth, can be 45 cm thick.

Either the entire floor mass or just the sruface layers (more economic) can be stabilized. The same additives are used as for the production of stabilized earth and the procedures are similar. Vegetable glues (e.g. white glue) can also be added. Stabilization considerably enhances the resistance to water and wear of earth floors.

Dry earth floors are traditionally hardened with animal (horse) urine and ox blood. Ox blood is sprinkled with cinders and clinkers and then beaten. Silicates of soda (floor not completely dry) or fluoscilicates (dry floor) can also be used. Sump oils or a mixture of turpentine and linseed oil will also serve the purpose. A clean finish can be obtained by using polishing wax.

2. Design details

(a) Preparation

Before constructing an earth floor the underlying ground must be prepared. The layer of earth containing vegetable material and humus is carefully cleared and all organic residues eliminated from it. The upper layer of the earth is rammed except when the soil is subject to swell or when its load-bearing capacity is adequate. The ground must be dry before the floor is begun.

(b) Waterproofing

An anticapillary barrier can be made with a layer of clayey earth 10 cm applied in the moist state in carefully rammed layers. Each layer must be dry and fine cracks filled before being covered. The top layer is finished with a flattening hammer after ramming. A bitumen or lime-stabilized sandy soil can replace the clayey soil. Stabilized earth or a plastic sheet can also be used. Whatever solution is adopted, the damp-proof membrane must rise up along the base of the wall.

(c) Stone filling

Dry-stone pitching, 20 to 25 cm deep, makes a good foundation. The largest stones are put down first, followed by tipped gravel. Dry stone can be replaced by gravel and coarse sand or by ballast.

(d) Insulation

The pitching is covered by an insulating layer, which can be a 10 cm layer of clay-straw. If this layer is too weak, it can be covered with a bearing course which distributes the loads.

(e) Load-bearing

This layer can be made of clayey earth mixed with cut straw or clay-straw containing hard and finely chopped straw (stalks 4 to 6 cm long) to which cement mortar is added, at a rate of one volume of cement for every six volumes of washed sand. The load-bearing layer should be 4 cm thick and always superstabilized so that it will harden after it has cured. Such curing sometimes requires moistening (damp sacks).

(f) Finish

A finish can be made with a thin layer of cement grout to which fine sand is added or has been given an oil-based treatment. A light filler in the form of sawdust can also be added to the grout. Proportions are as follows: one volume of sand, one volume of cement, one volume of sawdust. To mineralize the sawdust it is soaked beforehand in a lime or cement slurry and dried. The final stage of the finishing can be the colouring or waxing of the floor.

(g) Monolithic floors

Floors can be constructed using standard adobe mortar stabilized with bitumen. First the soil is properly prepared, then the mortar is poured and spread out with a screed after the floor guides have been positioned. Shrink cracks must be filled with a finer adobe mortar and the final touches are made with a trowel. After drying, the surface is treated with a mixture of turpentine and linseed oil and allowed to dry for a week before putting down the next layer. The floor can then be waxed and polished.

Earth-stabilized concrete mortar (one part cement to six to eight parts sandy soil) is also suitable. It is put down in a 5 cm thick layer marked out with pegs. Contraction joints must be left every 1.5 m. These must be deep and well defined (3 cm deep and 1/2 cm wide).

Other types of monolithic floors are constructed using rammed earth, sensitive to damp, stabilized rammed earth or rammed stabilized clay-straw. Insulation around the edge and a finishing screed (more costly) can also be provided. These earth floors are not attached to the walls. A flexible joint can be made in clay-straw.

(h) Floors made from elements

Earth-stabilized bricks or tiles can be laid on a 2 cm thick layer of mortar: one part cement to six parts of sandy soil. Care must be taken that the tiles adhere properly to the mortar. The joints can be filled with cement grout. The blocks used should be superstabilized or coated with a wearing layer. These blocks can also be laid on a layer of sand and the joints filled with sand.

B. Floors above ground level

1. Basic principles

The upper surface or covering must be durable, flat, pleasant to look at, easy to maintain and, in the case of flat roofs, water-tight.

The structure, woodwork or slab, must be able to support moving and static loads, resist point loads, be very rigid and transmit loads to the supports properly.

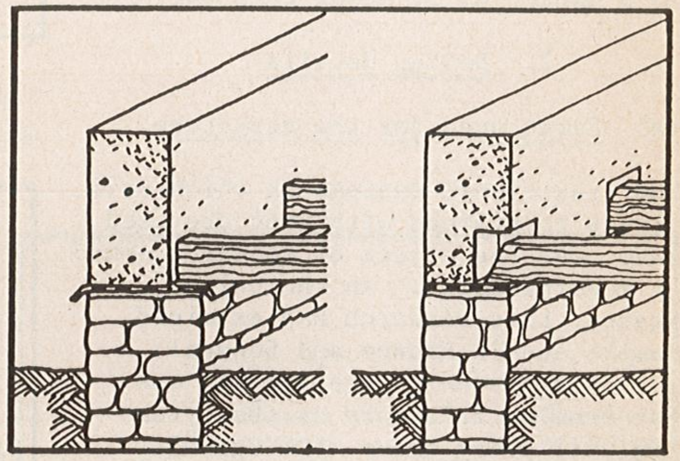
The underside, or ceiling must be pleasant to look at.

There are various solutions to the problem of the bond between floors and earth walls with support being either independent of the wall or on the wall.

(a) Support independent of the wall

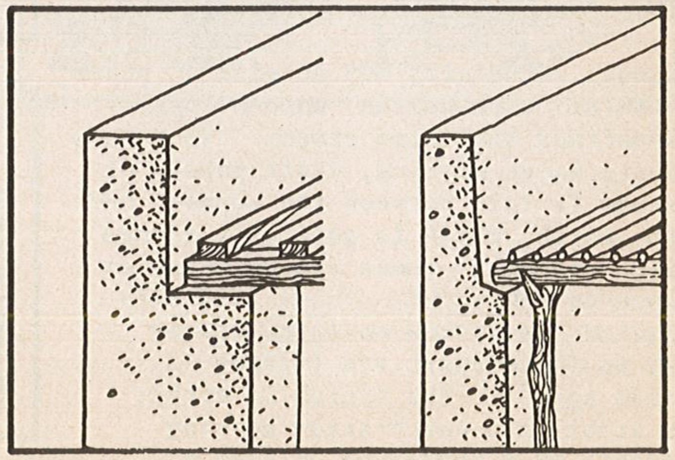
(i) On the foundations

Studs supporting the beams are fixed on notches on the foundation footings. This is satisfactory for floors above cellars or sanitary spaces even though fixing the studs may be difficult.



(ii) On the base course

This is made wider than the wall to take the beams. The base course must be levelled and the beams must not touch the wall. The base course can be widened more cheaply by locating beams in niches in the bottom of the wall, at base course level. Here too the beams must not touch the wall. In both systems a horizontal anticapillary membrance must be laid, and a skirting board fitted as finish. For reinforced-concrete slab floors it is best to use a widened base course since penetration of the wall by the slab will weaken the base of the wall.

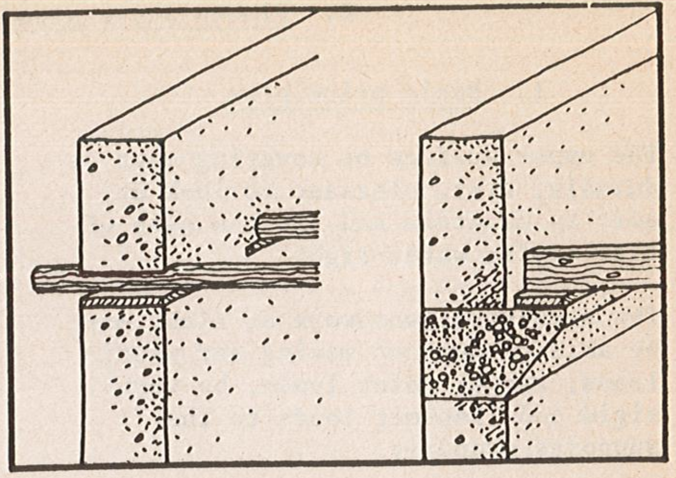


(iii) Beside the wall

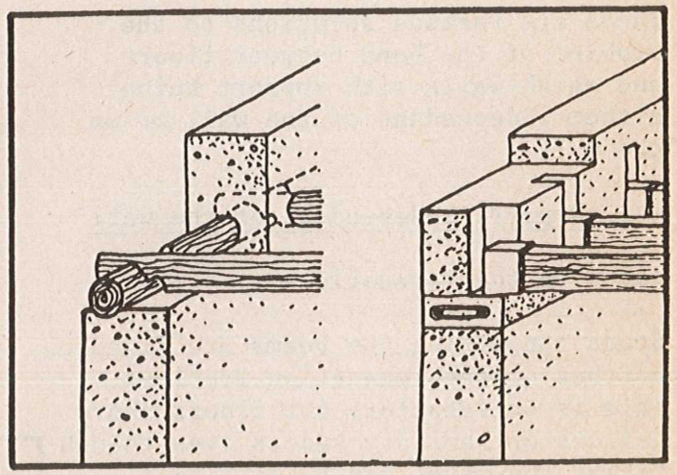
This method makes use of wooden corner pieces or masonry projections from the wall. This is the preferred solution for heavy floors and non-load-bearing walls. e.g., wattle filled in with clay-straw or cob.

(b) Support in the wall

In this system there are the following dangers: point loading (beams) or continuous weakening (slabs) of the wall, rotation of the support (excessive freedom of movement of the beams or sagging of floors), and different degrees of thrust on the wall.



Point loads should be distributed by the ring-beam or a carefully designed (weight of loads transferred at an angle of 45^{o}) wooden, stone or concrete sole plate or through ties. Space for the beams can be hollowed out or provided when building the walls. Treated wood should be used for wooden floors, and contact between wood and earth is to be avoided. Use a flexible material like bitumen, felt or water reppelent mortar.



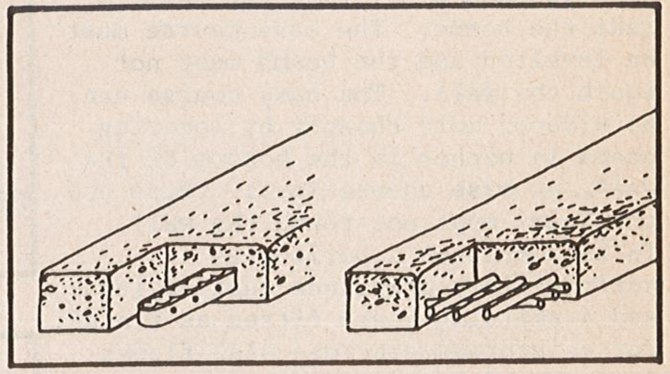
(c) Support on the side of the wall

The thickness of the wall is reduced where the floor passes through it. Here, too, care must be taken, with point beam supports or a ring-beam provided. Avoid placing the floor on a beam along the wall as there is a danger of it being torn out.

2. Design details

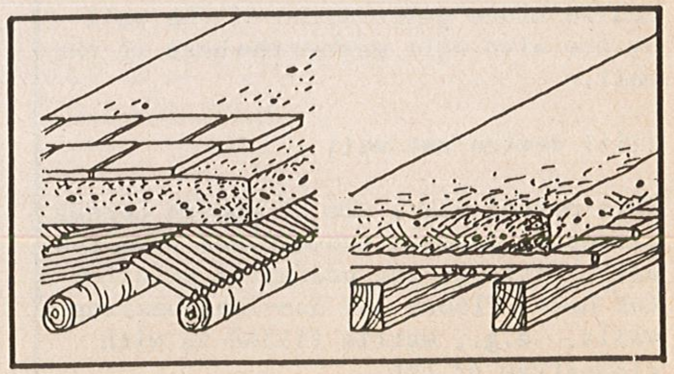
(a) Earth used for the structure

The traditional systems in which soil floors reinforced with wood are used have been the object of research aimed at modernization. In the United States, this research has examined bamboo and in France and Senegal galvanized steel. The results are far from satisfactory as the sytems are still very heavy (500 kg/m^3).



(b) Earth used for the surface

Wooden structures may consist of beams overlaid with boards, wooden logs or sometimes even flat stones. To reduce dust, woven matting, kraft paper, or straw is laid between the support and the earth, which is generally rammed (10 - 15 cm). These floors weigh as much as 250 kg/m^2. Those laid with packed clay-straw on laths spaced 10 to 15 cm apart are lighter (150 kg/m^2). The finish is either a stabilized earth-straw wearing layer, or a rendering or even a surface coating.

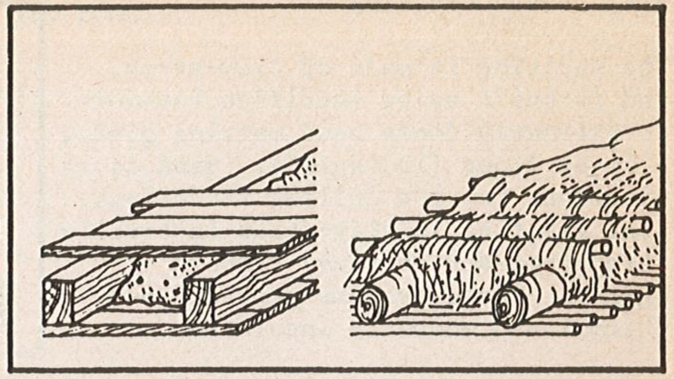


(c) Floors with earth infill

These systems are frequently used to enhance acoustic insulation.

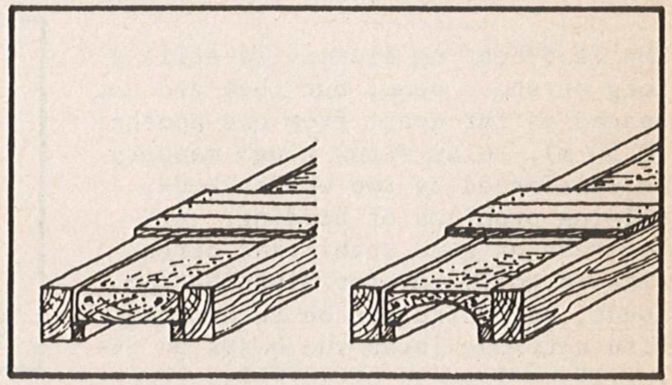
(i) Loose earth

Many wood joist floors and wooden board floors, with an underside of boards or reed screen, are packed or pugged with loose soil. The earth used should be absolutely dry.



(ii) Prefabricated panels

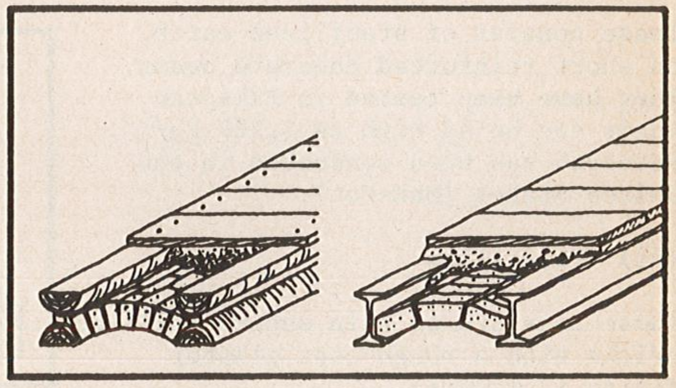
Usually these are made of daub or clay-straw and are used to fill the underside of the floor without adding to its bearing capacity. As a result, the distance between joists/beams can be quite large - 80 to 90 cm - and the prefabricated elements can be either short or long: 0.40 to 1.20 m for a thickness of 15 cm and a weight of from 35 Kg to 120 kg per element. The shape of the floor cavity makes it possible to lighten the floor.



(d) Vaulting and load-bearing infills

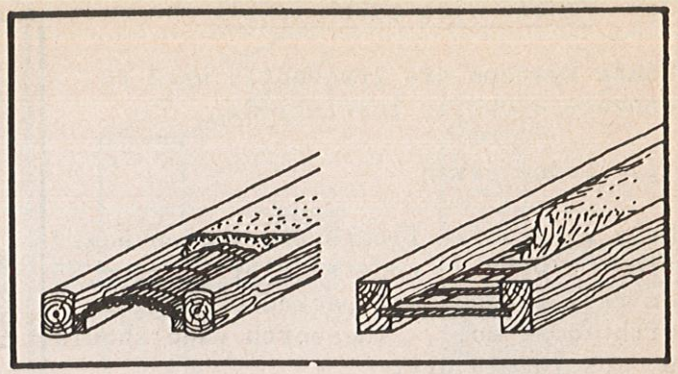
(i) Earth-brick vaulting

Floors constructed using brick vaulting put the soil in compression with bending stresses being taken up by beams in timber, steel or even reinforced concrete. The space between the beams ranges from 0.50 m for the smaller systems to 2 m for the largest ones, which sometimes require the use of metal ties. The brick vault rests on the lower flanges or the flanks of small beams. A slight deflection (1/10 of the span) allows the small beams to take up the stresses well. These systems are fairly heavy (400 kg/m^2). They can be constructed with formwork, usually slip forms, with the bricks being laid on edge or flat in two layers and with staggered joints; or without formwork, e.g., in Nubian style slanting bond. Lighter, perforated bricks and tiles, shaped to fit on beams, or procedures which rely on wedging and require no formwork can be used.



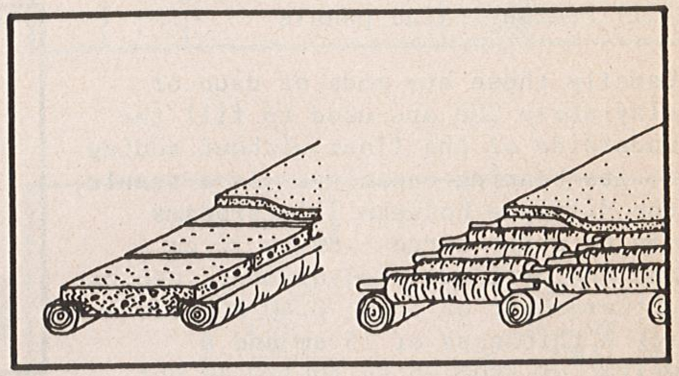
(ii) Cased vaulting

The vaulting is made of clay-straw, and is built using sacrifice formwork in extremely dense reed matting giving a light floor (150 kg/m^2). Reed is an excellent key for ceiling renderings. Flat vaulting in clay-straw internally strengthened with round timbers (220 kg/m^2). These systems provide good thermal and acoustic insulation.



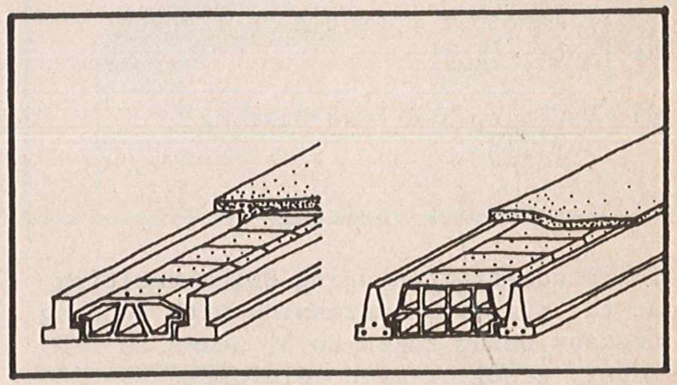
(iii) Prefabricated infills

The laod-bearing element is still a long or short beam, but they are not spaced as far apart from one another (0.50 m). Clay-straw rough masonry is reinforced by two wooden rods, solving problems of bending. A concrete or even stabilized earth slab (6 to 10 cm) for distributing loads, and which can be reinforced with netting, joins the beams to the infills. Instead of infills, earth reels in straw-clay can be used. These systems are light (150 to 200 kg/m^2).



(iv) Hollow infills

Made of compressed stabilized earth or extruded earth, this product is currently under test.



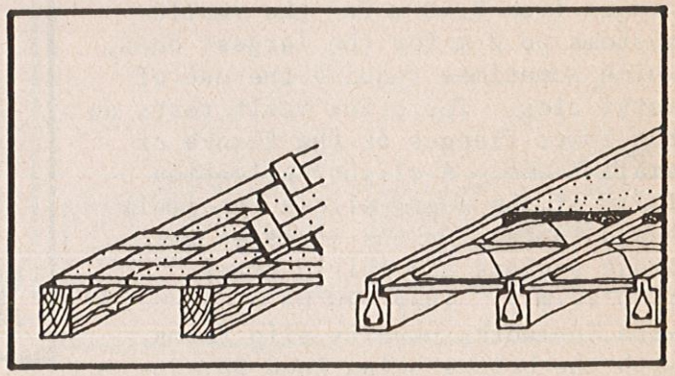
(e) Other systems

(i) Hyperbolic infills

These consist of stabilized earth, on short reinforced concrete beams. They have been tested in Pakistan. Loads can be as high as 1,220 kg/m^2. Research has been conducted in the United States (Max-Pot).

(ii) Thin tiles

These consists of thin superstabilized bricks with a rough-cast plaster finish (2 layers).



VI. ROOFS VAULTS AND DOMES

A. Flat roofs

1. Basic principles

Flat earth roofs are vey heavy, ranging in weight from 300 kg/m^2 to as much as 500 kg/m^2. They are therefore not suitable for use in earthquake-prone regions.

Flat earth roofs are particularly sensitive to water. Torrential rains can destory a roof. Care must thus be taken to ensure adequate waterproofing: special soils (kaolins, saline soils), stabilization, other watertight materials and, above all, appropriate design and constant maintenance.

Because of their immense thermal inertia, these roofs are suitable for hot, dry climates. If the roof requires insulation, stretched matting, loose straw, clay-straw or seaweed can be used. Limewashing increases solar reflection: 90 per cent compared to 20 per cent for roofs which are left before.

(a) Waterproofing

This can be accomplished using common materials, e.g., bitumen felt and plastic sheeting, or layers of rammed clayey earth, or of stabilized earth: e.g., a well-compacted lime screed. Bitumen felt or plastic waterproofing must be covered with soil to prevent ultraviolet damage. Drain water from roofs against the direction of the prevailing wind to prevent splashing. Waterproofing must be assiduously maintained.

(b) Gutters and downpipes

Care must be taken not to fix the roof gutters against the walls but instead along the eaves of the roof. Sections should be generous and have a steep enough gradient. Drain water from each section of the roof individually and allow it to escape at the end of a straight gutter. Never use a bend: as there is a danger of overflowing and blocking. Connect roof gutters directly into down pipes.

Use broad sections for downpipes and avoid fixing them against the wall. Do not use fragile or perishable materials (e.g., plastic).

Water should not be discharged at the foot of the wall: provide a rainwater shoe facing towards a drain or gutter. Do not place a rain-water barrel at the foot of the wall. Maintain the downpipes: attend to repairs without delay.

Downpipes built into or recessed into the wall should be avoided. Avoid decorative downpipes and descents: e.g., hanging chains because of splashing on windy days.

2. Design details

The main drawback of flat earth roofs is that the waterproofing is often defective. In traditional construction, special soils are used: powdered soil from termite hills (Africa), salt clay mud (the corak of Turkey) or soils to which natural stabilizers have been added: e.g., animal dung, shea butter. There are also systems where layers of sand and clay are alternated, to make a thick layer. These roofs are heavy and their water-tightness can only be guaranteed if the upper layers become saturated.

The quality of an earth roof depends above all on good execution. Ram the earth in several layers, seal all shrink cracks and compact by beating. Pebbles can be tamped into the surface layer. This makes a good wearing layer that is resistant to rain-impact erosion.

It is still preferable to decrease the thickness of the earth (less weight) and to treat or stabilize the soil. Regular maintenance is absolutely essential.

(a) Soil layers

If these soils are treated or stabilized, effective stabilizers must be used. Stabilization with bitumen is more effective for this type of job than with lime or cement.

(b) Renderings

A screed of lime and coarse sand, carefully sealed and in which the micro-fissures have been sealed by a regularly refreshed limewash is effective. Rubber-based paints can also be used, but one must be on guard for condensation in damp or poorly ventilated rooms.

(c) Bitumen felt

This can be placed under rammed earth which is then covered with pebbles and planted moss. It can also be fitted above the rammed earth but must be protected against heat with gravel. The connections with parapets and gulleys must be carefully maintained.

(d) Plastic sheet

A polyethylene sheet under the soil is just as effective as bitumen felt. The soil can be sown with grass with non-penetrating roots. The joints between the roof and the walls must be made with care.

(e) Paving, tiles, flags

Accessible roofs can be paved with all sorts of surfaces. The gradient must be steep enough to allow water to be effectively drained towards gargoyles and downpipes. Use a water-repellent mortar.

(f) Roof overhang

The function of a roof overhang is manifold: to retain the soil of which the roof is made, to decrease erosion at the top of the wall, to discharge water away from the base of the wall, to protect the surface of the wall against vertical rain, and to provide shade.

Wide eaves (at least 30 cm) are often encountered in traditional earth architecture. They provide greater stability and resistance to pressure differences caused by the wind. Such eaves can be fitted with gutters of generous proportions. These should be firmly fastened.

(g) Parapets

A parapet allows the roofing soil to be retained and gives greater control over the drainage of water from the roof by guiding the water to the gargoyles and downpipes. A parapet also serves as a railing for accessible terraces and affords effective protection against pressure differences due to wind. In addition, the parapet plays an aesthetic role. It should be heavy and constructed of durable materials and/or protected from erosion either by a coping (30 cm minimum) made of a conventional material (stone, brick, tile, reeds and earth) or by rendering, preferably waterproof. The upstands of damp-proofing against the parapet and around gargoyles should be very carefully constructed.

B. Pitched roofs

1. Basic principles

Pitched roofs with broad eaves (minimum 30 cm) drain rainwater very well and are particularly well suited to earth structures. These roofs are also suitable for use in tropical cyclone regions (minimum gradient, 30°). This applies in particular to hipped roofs (i.e., four slopes) which are preferable in such regions to gable roofs (two slopes).

Hipped roofs offer better protection against wind and rain and economize on wall material, but make the structure more complicated. These elaborate roofs are costly in materials and manpower and it is not unusual to see that the pitch is reduced. This reduces the surface area and economizes on the roof frame and decking.

Hipped and gable roofs make it possible to build "umbrella" and "parasol" structures erected before raising the walls and enabling the work to be carried out in a sheltered area. This system does away with the limitations of load and thrust on earth walls since the roof structure bears directly on the foundations and slabs. There is, however, a redundancy of structure and materials which are acceptable only in richer economies or in large construction projects.

The roof must be built rapidly and not too long after the rest of the construction work. If it rains during the construction of the roof, the top of the exposed walls must be well protected. One must always allow for the possible failure of the roof and make the top of the walls water-tight.

There is a suitable pitch for every roof covering. Reducing this pitch may lead to leaks as the result of inadequate drainage, standing water or infiltration by water.

Saw-tooth roofs are to be avoided as are roofs with two adjacent slopes having low edges, unless the use of wide sloping gutters is envisaged.

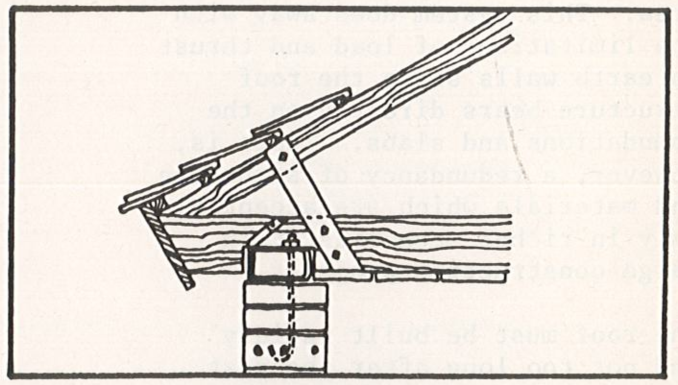
The joints of damp-proofing must be properly executed.

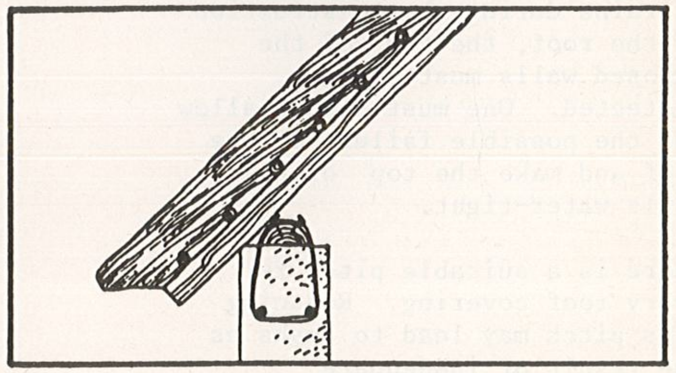
Walls of which the upper portion forms a gable are to be avoided as they make flashing and mortar infilling necessary and this is not always reliable. The flashing for roofs supported by gable walls should be executed by means of a strip of rendering or wearing surface consisting of stones or burnt bricks which affords protection against water splash.

Horizontal thrust must either be eliminated or properly taken up: there is a danger of walls bowing or of cracks around openings. Loads should be uniformly distributed on ring beams. Reinforce gables of structures with thin walls: reinforcement, ties, posts.

Anchoring pitched roofs

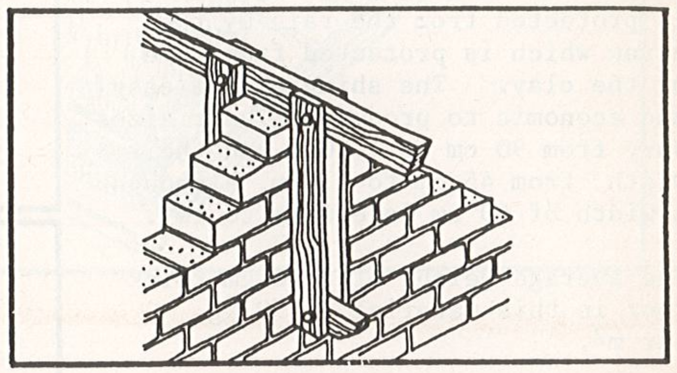
Ancoring roofs to walls is absolutely essential if the danger of causing deformation of the roofing and roof-loss in strong winds is to be avoided. This precaution is of cardinal importance in regions prone to tropical cyclones. As a general rule, the anchoring system must be very solid and properly designed. No economies on materials are justified. The roof must be fastened to outside walls, gutter-bearing walls and gable walls, but can also be anchored to dividing walls. If the structure of the building is reinforced with concrete or wooden posts, anchoring is fairly easy. It is, however, better to anchor roofs on continuous ties than on isolated supports.





(i) Anchoring on gutter-bearing walls

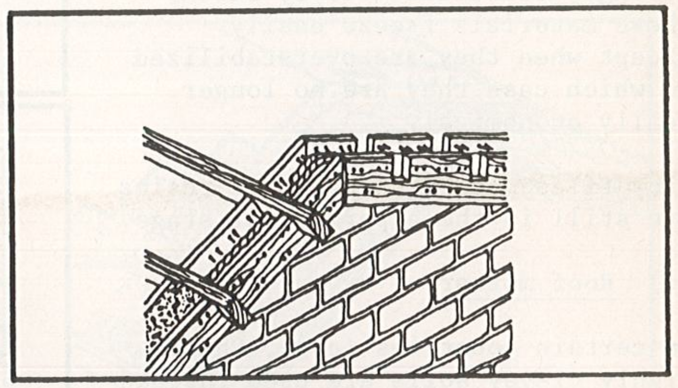
Wood. A wall plate on a gutter-bearing wall can also act as a ring beam as well as an anchor plate. This continuous wooden support must be extremely well secured: e.g., collars, anchor-bars bolted and fixed to the wall. When the ring beam is lower than the finished top of the levelling course below the roof on the gutter-bearing wall, the lower purlin can be fastened to the ring beam by clamps or metal or wooden beam ties. This same ring beam can be used to anchor corbels or metal shoes to receive a facing beam for a porch or verandah, even a future extension of the building (India).

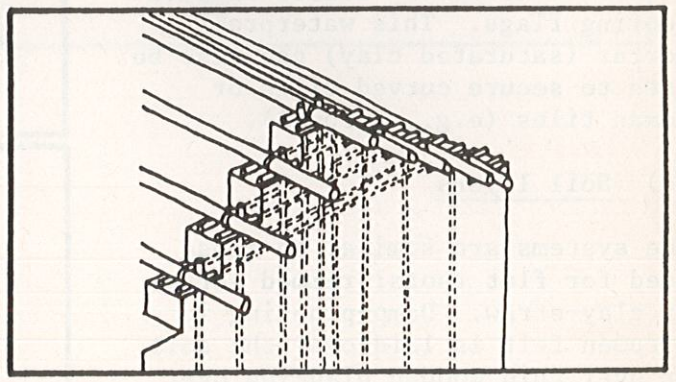


Concrete. A concrete ring beam makes it possible to provided iron ties for a lower purlin or roof beam.

(ii) Anchorage on gable walls

Hipped roofs are anchored to side walls in accordance with the principles already set forth. For gable roofs with purlins extending into the gables, the purlins can be anchored to the ring beam, which is an extension of the one in the gutter-bearing walls or an alternative ring beam at the height of the support of the purlins. Metal or wooden tie bars fixed to wooden corbels at the level of the ring beam can also be used, either above it (the weight bears on the ties) or below it (tensile stresses due to wind are exerted on the ring beam). This solution to the problem of anchoring to the ring beam avoids overloading the gable itself, which is the weakest wall in the structure. Systems incorporating clamps or wooden or metal ties increase the stiffness of the gable.



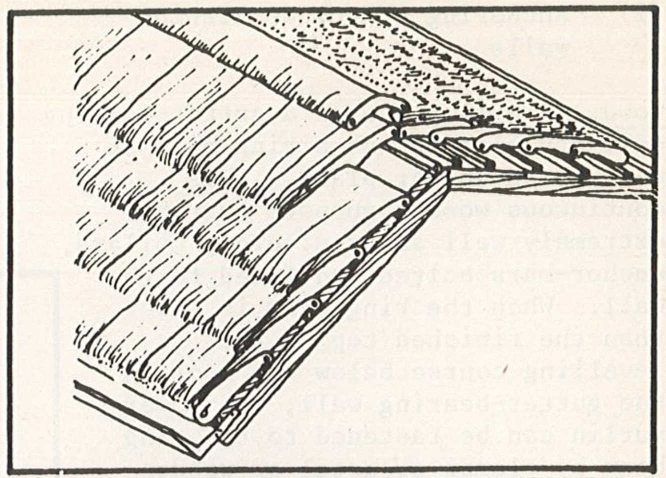


2. Design details

(a) Clay-straw shingles

These shingles consist of a layer of straw - visible on the roof - held in two layers of clay of which the second is visible on the underside. The clay is protected from the rain by the straw which is protected from fire by the clay. The shingles are easy and economic to produce. Their sizes vary from 90 cm to 1.20 m and their width from 45 cm to 1.5 m, although a width of 60 cm is easier to lay.

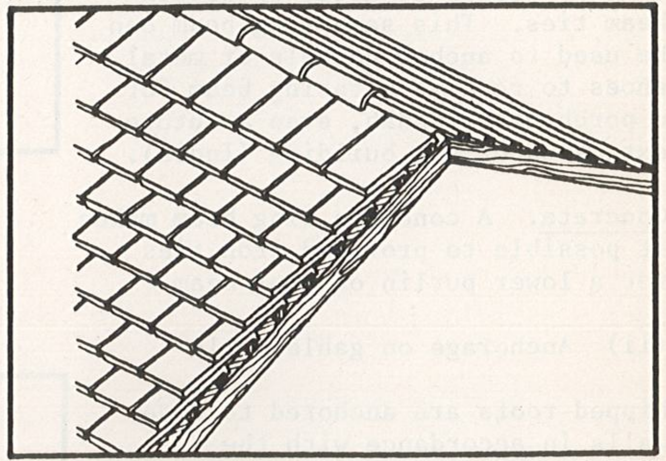
The average weight of a 20 cm thick roof in this material is 50 kg per m².

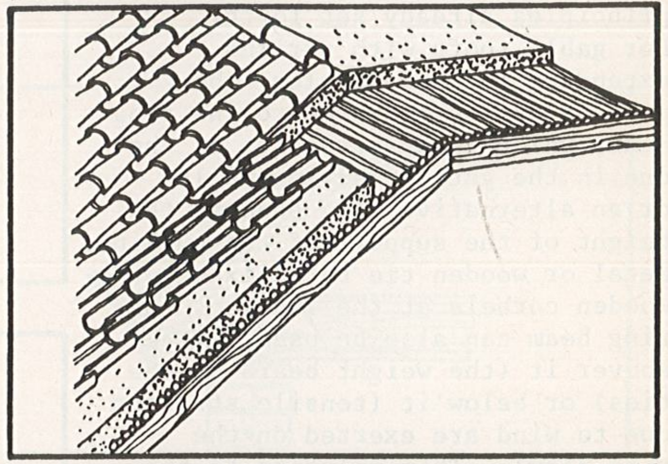


(b) Tiles

Two types of tiles are used: flat single-lap tiles (e.g., Brazil) and curved tiles (e.g., France) in strongly stabilized clayey earth. These materials freeze easily except when they are overstabilized in which case they are no longer really economical.

Clay tiles made with phenolic resins are still in the experimental stage.



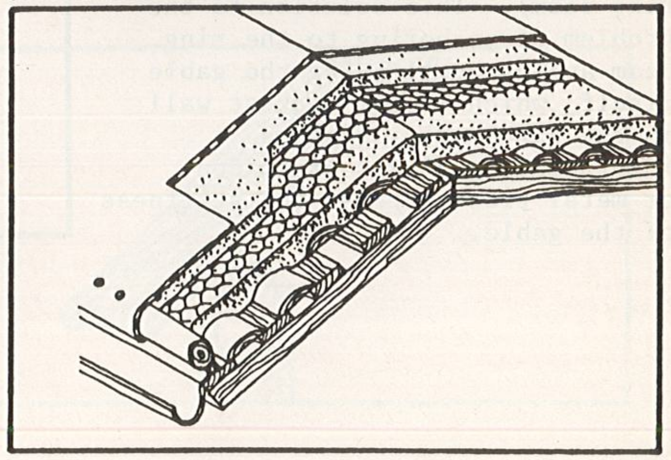


(c) Roof mortar

In certain countries (e.g., China) highly clayey soils are used instead of mortar to secure slates or even roofing flags. This waterproof mortar (saturated clay) can also be used to secure curved tiles or Roman tiles (e.g., Burundi).

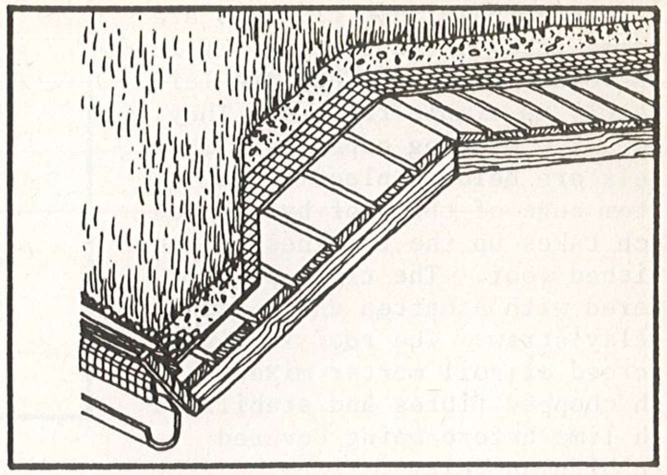
(d) Soil layers

The systems are similar to those used for flat roofs: rammed earth or clay-straw. Damp-proofing in bitumen felt is laid over the soil or over thin wooden planking over the soil. There are also roofs made in bitumen-stabilized clayey earth reinforced with a netting (screed or shingles). These roof claddings are heavy.



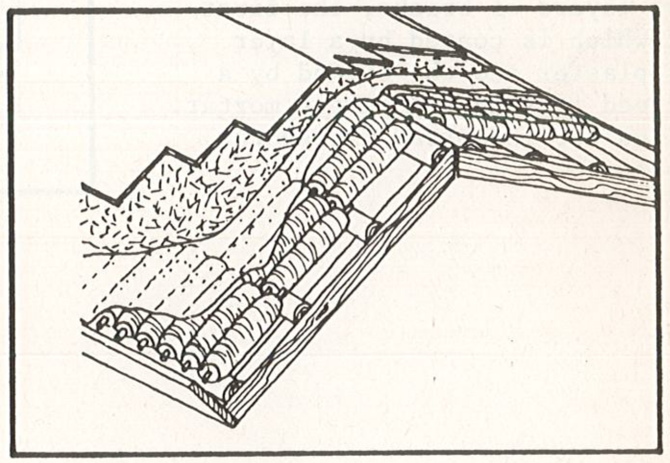
(e) Grass roofs

Such roofs have several advantages: purification of the air indoors, thermal insulation and buffering, control of indoor comfort by condensation and evaporation, and sound-proofing. The thickness of the soil in which the grass grows is at least 20 cm resulting in heavy loads (strong absorption of water), making it necessary to design a special roof frame. In traditional systems, treated wood or flat stones covered with bitumen were used. Nowadays plastic damp-proofing is available which is put down in a single layer without joints. This type of damp-proofing must be non-flammable and able to stand up to solar radiation. The pitch of this type of roof lies between 5° to 45°, an angle of 20° being preferred as this pitch greatly faciliates drainage.



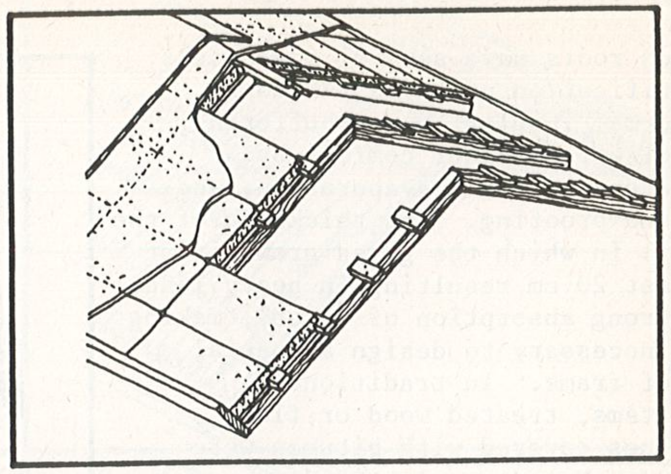
(f) Earth reels

These consist of a clayey soil mixed with long fibres and rolled around spindles in the form of reels. The resulting reels are laid between the purlins when still moist and pressed against one another. The spaces between the rows of reels are packed with daub. After drying, the cracks are filled with clay and applied with a mop. A 2-cm thick layer of soil mortar, stabilized with finely chopped fibres and lime, is then applied. This layer is then covered with roofing felt which is in turn covered with sand. This type of roof weighs about 200 kg/m² (including the frame which is on the light side). Its use is not recommended in areas infested by termites.



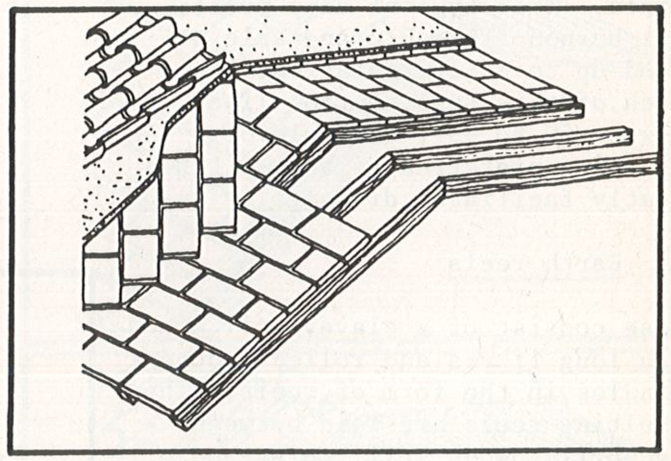
(g) Panels

These relatively thin elements are in clay-straw or daub and reinforced with wooden sticks. They are laid directly on simple rafters. They have a low bearing capacity. The panels are held in place on the bottom edge of the roof by a board which takes up the thickness of the finished roof. The ridge pole is covered with a batten and a layer of clay-straw. The roof is given a screed of soil mortar mixed with chopped fibres and stabilized with lime before being covered with bitumen felt.



(h) Brick roofs

This uses the principles of the tile floor. It is built in small flat bricks given a rough-cast of plaster. Both the bricks and the workmanship must be of a high standard. The system consists of two layers of bricks, the first of which is coated by a layer of plaster and the second by a screed in sand and cement mortar. Tiles set in mortar finish the roof.



C. Vaults

1. Basic principles

(a) Marking out

Mathematical design methods can be used. However, e.g., for the catenary arch, it is more practical to construct a plot by using a light chain. The span and the rise are predetermined by three points in a vertical plane through which the chain must pass. The curve which is plotted is inverted and it must be confined to the middle third of the thickness of the vault. The shape of the formwork must be corrected to the required thickness on each side of the curve.

Dimensions

(i) Span

Vaults with spans of up to 6 m and 15 cm thick have been built in stabilized compressed blocks; whereas spans of vaults in rammed earth rarely exceed 2.5 m. In the Islamic Republic of Iran, the most commonly found span is 4 m. This is the maximum for earthquake-prone regions, and for such regions it has also been established that the ratio of span to length should be equal to 1.5 x width. If the value of span to length is greater than this, there is a danger that the vault will resonate and shatter (according to research conducted by the University of Baja California, Mexico).

(ii) Rise

The less the rise, the greater the lateral thrust, the greater the rise, the lower the thrust, approaching a limit value of zero. For catenary vaults the conventional ratio of span to the rising indicates that the rise should be equal to 50 cm plus half of the span. In earthquake-prone zones it is advisable to limit the rise to between 20 and 30 per cent of the value of the span.

(iii) Thrust

If the rise is very large the thrust on the walls can be enough to cause them to collapse. The methods used to determine the dimensions of arches and piers can be used to determine the dimensions of walls. Above all wall bases and wall foundations must be carefully designed. There are several ways of ensuring the stability of vaults:

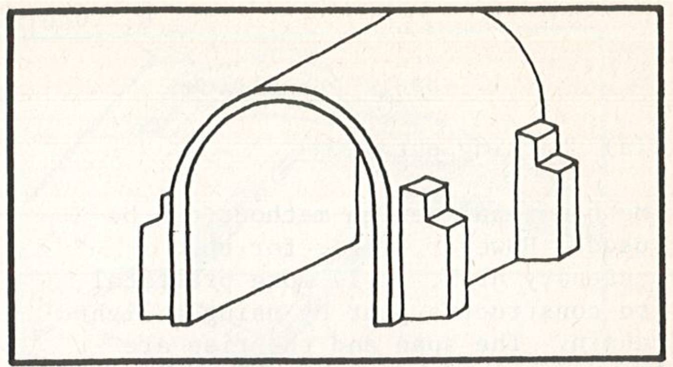
(a) Thick walls: these require a great deal of material and should not be weakened by large openings;

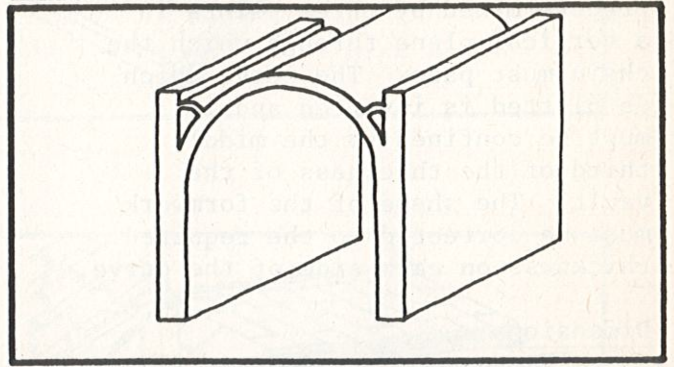
(b) Buttresses which must be supported by good foundations linked to wall foundations;

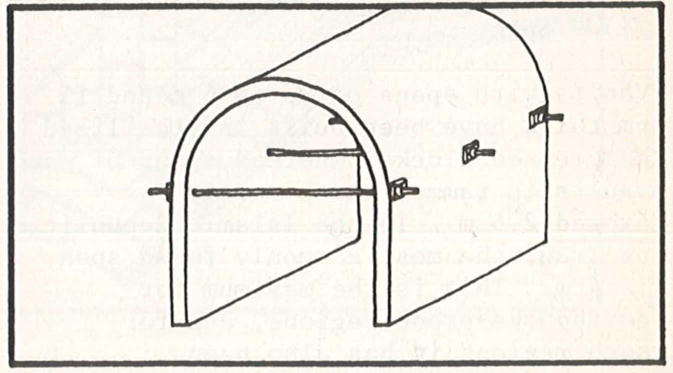
(c) Prestressing load (parapet or principle), which transform lateral thrust into vertical thrust;

(d) Tie bars which eliminate thrust; these must be evenly distributed and securely anchored;

(e) Tying taking up thrust and which should be able to resist the bending forces induced by thrust.





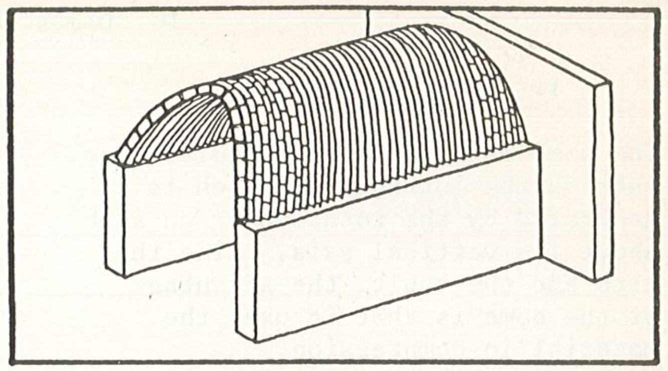


(b) Waterproofing

This is the major problem with vaults in regions where rainfall is heavy, due to infiltration through fine surface cracks (result from expansion in repeated hot and cold cycles), and inadequate drainage at the crown and haunch (water accumulates and permeates the material: the slope must be made steeper). Vaults must be carefully protected from rain by means of damp-roof renderings, such as washes, bitumen felts, elastic paints, and by regular maintenance.

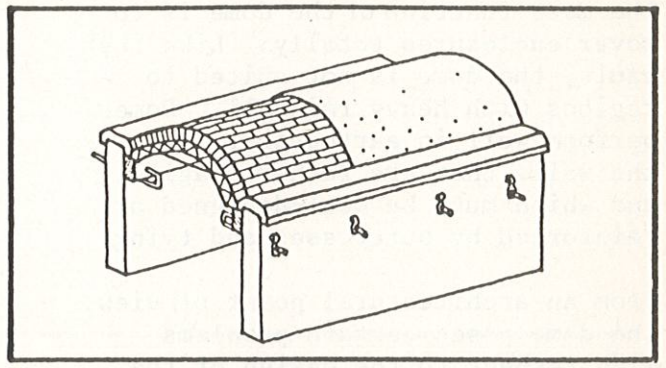
2. Design details

(a) Bricks - without formwork



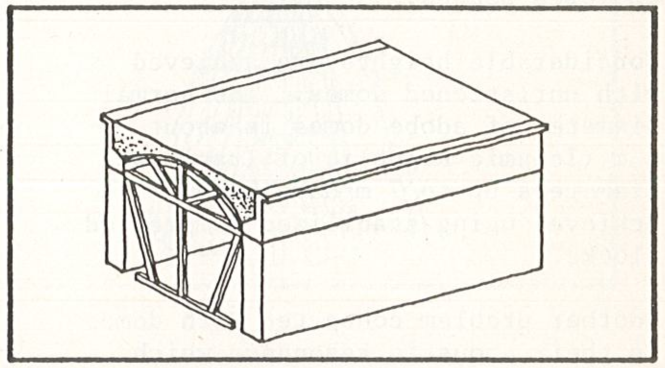
The "Nubian-style" method exploits the mutual friction of the bricks and the adhesion of earth mortar, the courses being inclined at an angle of between 10° to 15°. The bricks must be light (e.g., adobe rich in straw) and not thick (5-6 cm). Thin compressed blocks with grooves to enhance their adhesion can also be used. The main difficulty is respecting the curvature and (confinement to the middle third). A template for the construction is essential for inexperienced builders.

(b) Bricks - with formwork



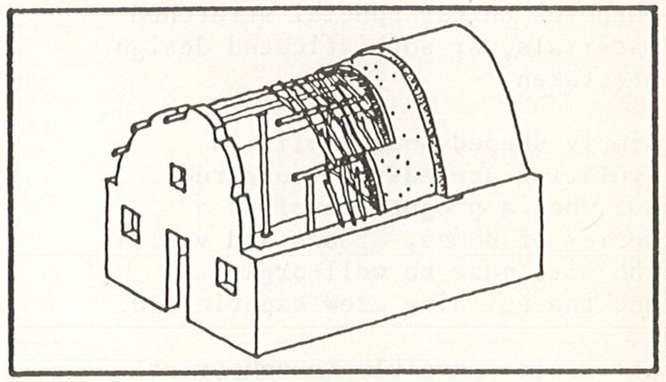
The formwork makes it possible to work parallel to the walls. It can be heavy and fixed or light and sliding. In the latter case, the builder proceeds in successive layers of bonded bricks or even in rings. The setting of the keystone of the arch must be carried out with care.

(c) Rammed earth on formwork



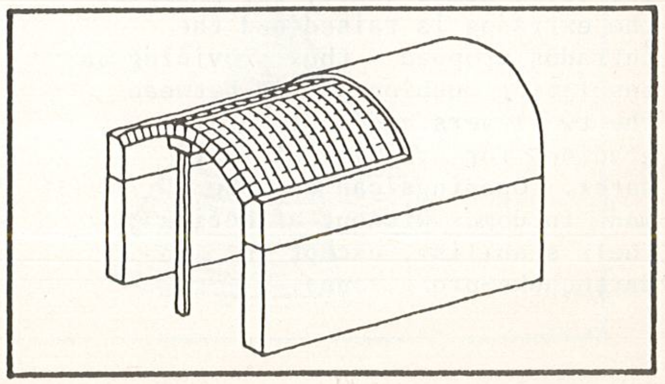
Although rarely used, this construction system does exist. Monolithic arches made of rammed earth and on formwork are generally dropped and held in position by ties. The layer of earth above the extrados is given a gradient. The formwork is very heavy and fixed (ramming stresses) and cannot be used for several days.

(d) Mud over frame



An arched structure consisting of interlaced branches is covered with mud to which cow dung has been added. The rigidity and water-resisting qualities of the system are precarious.

(e) Prefabricated elements



Hollow elements are prefabricated by double-acting hydraulic presses. The system is highly sophisticated and requires the use of concrete bars to provide the prefabricated vault with a high degree of stability. The vault is assembled in small half vaults assembled on a ring.

D. Domes

1. Basic principles

The dome is a vault of circular cross section the intrados of which is generated by the rotation of an arch about its vertical axis. Like the arch and the vault, the advantage of the dome is that it uses the material in compression.

The most function of the dome is to cover enclosures totally. Like the vault, the dome is not suited to regions with heavy rainfall. Domes perform well in earthquake; it is the walls that are rather fragile, and which must be well-designed or reinforced by buttresses and tying.

From an architectural point of view, the dome poses certain problems with respect to the design of the enclosed spaces.

Considerable heights are achieved with unflattened domes. The normal diameter of adobe domes is about 4 m (Islamic Republic of Iran), but diameters up to 7 m have been achieved using stabilized compressed blocks.

Another problem connected with domes is their acoustic resonance which renders them unsuitable for certain purposes unless special stretched materials, or sophisticated design, are taken.

Simply shaped domes built in isolation are easy to construct, but when a project involves a series of domes, arches and vaults, the site must be well-organized and the building crew experienced.

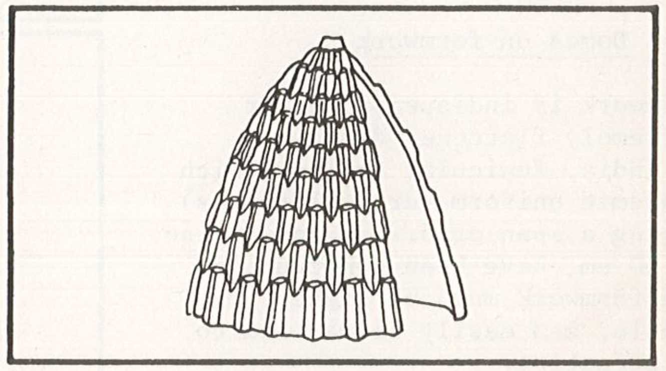
It is also possible to construct two-layer domes where, for example, the extrados is raised and the intrados dropped - thus providing an insulating cushion of air between the two layers and a better gradient for draining off rain water. Openings can also be made in domes without affecting their stability, except in earthquake-prone zones.

Traditionally, domes are waterproofed with a screed (e.g., bitumen, lime) or by surfacing with burnt brick and ceramic tiles (e.g., Islamic Republic of Iran).

The supporting structure can vary greatly depending on the plan. The height of the walls, the diameter of the dome and its centering must be adapted to this. A spherical dome on a circular plan poses no problems, but square, rectangular or pentagonal plans give rise to complex setting out and necessitate the construction of intermediary supports such as squinches and pendentives.

2. Design details

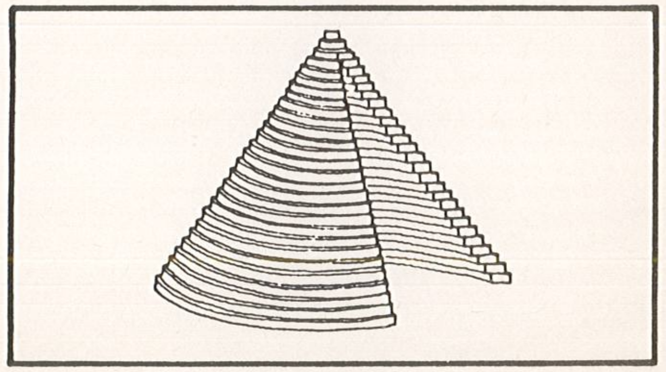
(a) Monolithic domes



These are domes built by hand, using pottery techniques adapted to architecture. A case in point is the famous shell-shaped dwellings of the Mousgoum tribe of Cameroon. Examples of this are becoming increasingly rare. They consist of a highly cohesive specially prepared earth shell, 15 to 20 cm thick at its base, 5 cm thick at the top and 7 to 8 m high. It is constructed without scaffolding, but a surface relief gives footholds while at the same time dividing run-off effectively reducing erosion.

Modern versions using rolls of extruded earth have been tested in the Federal Republic of Germany, where the construction of a rammed earth dome has also been tried with success.

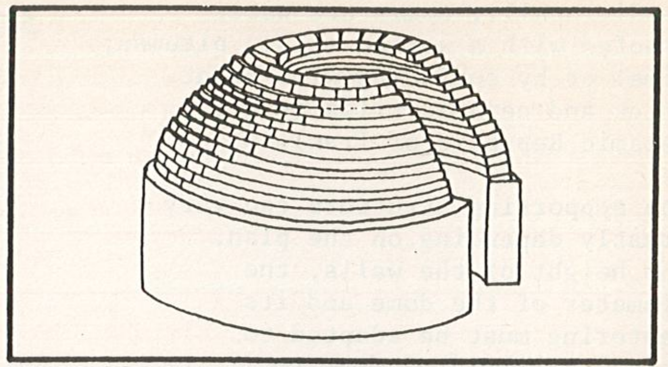
(b) Corbelled domes



These are erected by building inwards on successive horizontal courses, which hold together due to the adhesion and cohesion of the matter. This principle has been adapted to conical and pyramidal shapes (projects in Honduras in the 1980s), but the execution is very slow since it is necessary to stop for drying every two or three courses of bricks.

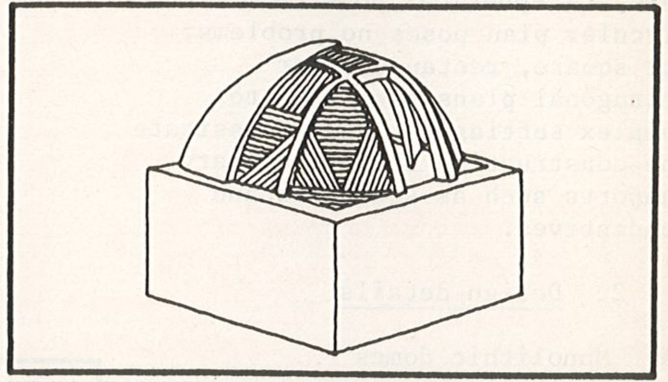
(c) Domes with inclined courses

This involves the construction principle developed by traditional Nubian architecture (Upper Egypt) and adopted in designs by Hassan Fathy (village of New Courna project). The construction system is very cunning and rapid.



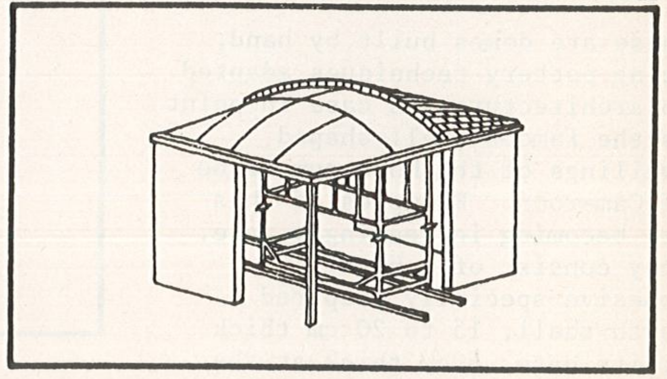
(d) Domes on sacrifice formwork

This method is typical for the architecture of Niger and Nigeria, among others. The dome is built using brushwood and small branches and then covered with earth, which makes the structure rigid and waterproof. Inside the wood ribs are also covered with earth.



(f) Domes on formwork

Formwork is indispensable for extremely flattened domes. In India, funicular shells (which transmit uniform vertical forces) having a span of 5.20 m and a rise of 60 cm, have been constructed. The formwork must be light, mobile, and easily dismantled to be effective.



VII. FIREPLACES AND SERVICES

A. Fireplaces

Earth can be used in an immense variety of applications, including the construction of kilns and furnaces, fireplaces and flues. Such equipment functions well but requires regular upkeep, without which it is liable to deteriorate rapidly. Burnt earth materials are better suited to building such items and are clearly more durable. The use of earth as a monolithic material, e.g., rammed earth or cob, is acceptable, but is not recommended for making fireplaces or flues, because of cracking and shrinkage problems. Stabilized compressed bricks or very compact adobes are serviceable.

There are two possibilities for using earth to build fireplace: either the hearth and fireplace surrounding it are constructed using sun-dried earth, or the fireplace is constructed using burnt materials and the hearth built in raw earth. If the earth is very clayey, the firing of the fireplace flue will cause shrink cracking which must be plugged with the greatest of care. If the earth is less clayey, the heat will cause drying and the material will lose its cohesion and become friable. These are the problems associated with burning at low temperature; a temperature ranging from 600° to 900°C is necessary to produce a quality burnt material.

While it is true that the inner facing of kilns can be made in raw earth as opposed to the outer facing for which burnt material is necessary, it is also true that firebacks must be made of refractory material. Internal cracking in a kiln is acceptable; it is less so in the case of an indoor chimney. The mortar used can be made from unstabilized earth to which ground burned brick has been added, the latter serving as sand. All of the cracks in the hearth must be plugged with care. Flues in unburnt earth are not recommended. Earthenware incorporated into the thickness of the walls or built outside, i.e. external flues, is preferable. This precaution guarantees the stability of the flue and helps to prevent noxious gases from escaping through the cracks. Inside, ducts can be rendered in raw earth but chimney pots on the roof should be in burnt brick.

No fire can be kindled until the masonry of the oven or fireplace has completely dried. The first fire should be moderate and slow-burning; an intense fire is liable to damage the structure. Cooling should also proceed slowly. With the second firing, the temperature should be raised slightly so as to bring about controlled smoking, e.g., with wet leaves, at the end of burning when the fireplace is hot and has expanded. In this way any possible escape of smoke can be detected through cracks which must then be plugged. Where earth and metal meets, e.g., at the cover of the oven, a little salt can be applied, since heated salt hermetically seals cracks.

B. Services

1. Plumbing

The installation of supply and drain pipes in earth homes must be carried out with special care, as constant moisture can have very serious consequences. In principle, every attempt should be made to centralize the plumbing to the greatest possible extent so that it can be easily examined and maintained, while avoiding the risk of defects which would be difficult to locate.

All waste water must be carried outside the house well away from the foundations. Gutters and manholes must be carefully maintained.

Inside the house, attention must be paid to the fittings in rooms containing plumbing installations: kitchen, water closets, and bathrooms as there is a considerable likelihood of damp. They must be ventilated and provided with easily accessible floor drains. Floors must be adequately sloped for drainage. The showerbaths must stand away from earth walls and these must be protected by a ventilated waterproof coating (danger of condensation).

Attention must be paid to ducts that may cause condensation, e.g., those for air conditioning and heating. It must be possible to drain any such condensate away. The slope of ducts and drip channels must be adequate or else the ducts must be insulated.

The incorporation of pipe and ducts into earth walls is not advisable. The best course is to make use of some part of the structure which is to make use of earth (stone or concrete base courses, vertical and horizontal tying, wooden frames) for securing them. Such fastenings must be carefully constructed to prevent leaks.

The anchoring points of pipes, ducts and appliances must be planned in advance. Wooden blocks of a good size firmly anchored in the walls will allow the fastening of brackets, hoods and rings. Wash basins, sinks, water-heaters expansion tanks etc., can be fixed on, for example, ventilated wooden structures. Walls must be protected against any possibility of splashing by using protective facing and plinths.

2. Electricity

An earth house, like any other house, is supplied with electric power by means of a connection with the existing mains.

If the mains supply is underground, connection poses no problem and can be effected at terminals and in cabinets (external meters). In the case of large housing complexes the connection of the electrical networks to the houses must be worked out in advance.

When the mains supply is from overhead wires, the problem of the connection of the mains supply to the house requires careful attention. The wires are very heavy, and once they are taut, induce tensile stress and vibrations. Consequently, the anchoring of mains supply brackets directly to the earth walls themselves is not recommended. They should rather be anchored to parts of the house that can resist tensile stress, e.g., vertical and horizontal ties.

It is advisable to incorporate sheathed wiring as well as all shielded conductors into the thickness of the floor screeds (widespread practice) or into "hard" base courses where recesses or anchoring points will have been provided. Maximum use must be made of materials other than earth for fastenings: e.g., the wooden framework in clay-straw structures. Generally speaking, grooves should not be made in earth walls for wiring but this is a viable solution if a rendering is provided. In that case the grooves are plugged with earth or mortar and finished with rendering on netting. It is wise to make use of plinths and door frames or to provide a cable duct on the ring beam or in the thickness of floors.

Switches and sockets can be flush-fitted or surface mounted. If they are flush-fitted they must be very deeply embedded; a properly designed fitting must be used for this purpose. The bedding can be in plaster. Surface-mounted fittings should preferably be installed on the base course, on plinths, on the subframes of openings, and vertical wooden frames. When mounting fittings on earth walls, small wooden blocks integrated in advance in the walls and embedded in deep plaster should be provided for mounting purposes.

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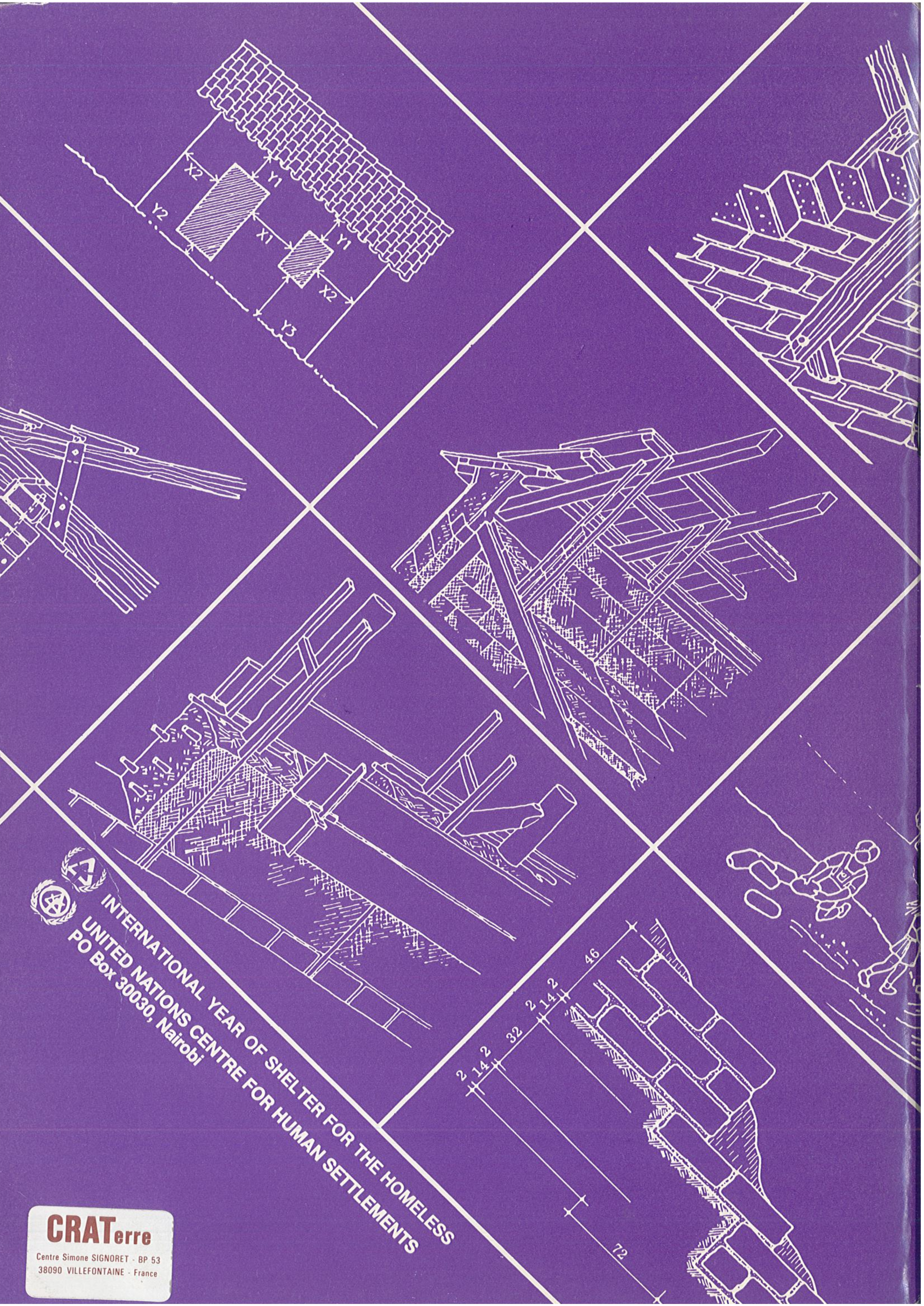

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